IMMERSIVE FUTURES

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Daniel Sjölie

Immersive Futures

Daniel Sjölie[1,,*]

1. University West

* *Correspondence:* Daniel Sjölie daniel.sjolie@hv.se

This book was created with significant assistance from AI tools.

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Preface

Welcome to "Immersive Futures," a comprehensive guide to immersive technologies and their applications. This book explores the world of Extended Reality (XR), including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), and examines how these technologies are reshaping our interaction with digital content.

What This Book Covers

This book provides a thorough exploration of immersive technologies, covering:

- The fundamentals of immersive media and the concept of presence
- The reality-virtuality continuum and various XR technologies
- Methods for creating and designing virtual environments
- Dynamic simulations and interactive virtual worlds
- Spatial interaction design principles
- Applications of XR across various industries
- Reality capture techniques
- The integration of artificial intelligence with XR technologies

Whether you're a student, researcher, developer, or industry professional, this book offers valuable insights into the current state and future potential of immersive technologies.

How to Use This Book

Each chapter builds upon concepts introduced in previous sections, but they can also be read independently based on your interests. Practical examples, case studies, and references to current research are included throughout to provide context and deepen understanding.

This book serves both as a textbook for courses on immersive technologies and as a reference for professionals working in XR-related fields.

HTML version

Updates

This section tracks significant changes and additions made to *Immersive Futures* to keep the content current with rapidly evolving XR technologies and teaching practices.

November 2025: Practical Implementation Additions

Based on comprehensive feedback from university teaching use, new practical implementation sections were added to Chapter 4 and Chapter 5 to provide concrete, testable Unreal Engine Blueprint workflows.

Chapter 4: Dynamic Virtual Environments

- **Collision Meshes**: New subsection explaining collision mesh concepts, simple vs. complex collision, and workflow for adding collision to imported assets from sources like Twinmotion. Addresses common student issue where physics "doesn't work" due to missing collision meshes.
- **Simple Animation in Unreal**: New section introducing Timeline component and Level Sequencer for animating interactive objects. Includes YouTube tutorial showing sliding door implementation with Timeline keyframes, overlap events, and Blueprint node connections.
- **Blueprint Variables and References**: New section introducing variable fundamentals (Boolean, Integer, Float types) with practical switch-controlling-door example. Includes YouTube tutorial demonstrating variable creation, Get/Set nodes, public vs. private variables, and Blueprint-to-Blueprint communication through references.

Chapter 5: Spatial Interaction Design

- **Constrained Manipulation**: New major section on levers, switches, and sliders using manual hand tracking approach. Covers Event Tick-based continuous tracking, constraint mathematics, and step-by-step rotational lever implementation. Includes links to complete Blueprint examples for rotational and linear controls.

Impact: Over 750 lines of new practical content added, focusing exclusively on Unreal Engine workflows. All sections include troubleshooting guidance, common variations, and align with actual course exercises. Two YouTube tutorials integrated with embedded players and QR codes.

2025: New Content and Structural Additions

Chapter 9: Societal Impact and Ethical Design

New capstone chapter (see Chapter 10) consolidating previously fragmented ethics discussions:

- **Psychological Impact & Embodiment**: Virtual embodiment implications, body ownership manipulation
- **Privacy, Consent & Data Governance**: GDPR considerations, biometric data concerns, consent protocols
- **Bias, Fairness & Representation**: AI bias, stereotypes in generated content, inclusion
- **Accessibility & Inclusive Design**: Physical and cognitive accessibility for XR experiences
- **Emerging Concerns**: Deepfakes, BCIs, emotional AI, digital rights
- **Ethical Framework**: Practical guidance for XR developers

Immersive Learning Theory

New subsection bridging Chapter 1 presence concepts with educational applications:

- Experiential Learning (Kolb's Cycle) and how VR uniquely enables it
- Situated Cognition and providing authentic learning contexts
- Cognitive Load Theory and VR's dual nature (reducing/increasing load)
- Explicit cross-references to theoretical foundations

AI Collaboration Documentation

Guidance on documenting generative AI use in XR development, covered in Chapter 8 and Chapter 10:

- Practical methods: conversation logs, iteration tracking, decision documentation
- "Thought partner" vs. "thought substitute" distinction
- Professional practice framing (not just academic compliance)
- Cross-referenced between technical and ethical contexts

Appendix: 2025 Technology Updates

Tracking document for emerging technologies and hardware not yet integrated into main chapters.

2025: Hardware and Technology Updates

Android XR and Gemini Integration

Updated coverage in Chapter 2 emphasizing Google's Gemini AI as core component of Android XR ecosystem, highlighting AI-native approach to XR platform design.

Bigscreen Beyond Coverage

Clarified coverage in Chapter 2 of Bigscreen Beyond and Beyond 2, noting the high-end PCVR positioning and custom-fit approach.

XR Headset Landscape

General updates in Chapter 2 reflecting 2025 hardware landscape, including discontinued products and new entrants.

2025: Narrative and Style Improvements

First-Person Voice Revision

Systematic revision removing third-person self-references throughout the book. Changed "The author" or "we" to direct first-person "I" where discussing personal experiences, research, or teaching approaches. Maintains appropriate academic tone while improving clarity and reader connection.

Lecture Quote Integration

Refined integration of lecture-based content, converting standalone blockquotes into narrative flow. Preserves authentic teaching voice while improving readability and maintaining context.

Section Reference Updates

Comprehensive cross-reference validation and updates across chapters, improving navigation between related topics (gesture recognition, voice interaction, volumetric video, medical training applications).

2025: Multimedia Integration

YouTube Video Embedding System

Implemented custom Quarto shortcode for YouTube video integration with:

- Comprehensive descriptions enabling content discovery
- Embedded players in HTML version and links in PDF version
- Consistent formatting across all video references

Video Content Expansion

Added AI-focused deep dive in Chapter 8 on audio technologies, including spatial audio, voice recognition, and AI-driven speech processing in XR contexts.

Image Licensing Compliance

Systematic review and replacement of images without clear licensing, ensuring all visual content meets academic publication standards.

Ongoing Development

This book continues to evolve with XR technology and teaching practice. For the most current version and updates beyond this publication date, visit github.com/dsjolie/ImmersiveFuturesBook.

1 Introduction to Immersive Media

1.1 Defining Immersive Technologies and XR

Immersive technologies enable us to interact with digital content in natural, intuitive ways, often blurring the line between the physical and virtual worlds. At its core is the concept of "presence" - the feeling of being physically present in a non-physical world. This sense of presence is a key factor in creating compelling and effective immersive experiences.

The primary goal of immersive media is to create experiences where our bodies and senses interact with digital environments as naturally as they do with the physical world.

My fundamental approach to immersive media centers on a simple principle: the goal is to get the brain to work "as if" in a real environment.

This embodied interaction can be so compelling that users may instinctively react to and interact with virtual objects as if they were physical. This is the basis for the potential of VR in training, education and engaging entertainment, as well as rich and natural interaction and communication in all kinds of applications, including social virtual worlds and professional meeting environments.

Figure 1.1: VR user engaged in a virtual environment, showing delight.

Immersive media encompasses a spectrum of technologies known as the virtuality continuum, ranging from our familiar physical reality to fully immersive virtual environments. More about this spectrum and related concepts in 2.1 The Reality-Virtuality Continuum, but the key common terms are, briefly:

1. **Augmented Reality (AR)**: Augments the real world by overlaying digital informa-

tion or objects onto it.

2. **Mixed Reality (MR)**: Mixing the real and virtual, in different ways. (More later).
3. **Virtual Reality (VR)**: Immerses users in a completely virtual environment, allowing for full-body interactions in a digital space.

XR is most commonly used as an umbrella term to cover all of these technologies. As they have significant overlap the same people are often interested in and working across these boundaries and we often want to talk about them as one type of technology - XR.

The power of immersive media lies in its ability to engage our senses and leverage our innate understanding of spatial relationships and physical interactions. By doing so, it creates more intuitive and engaging ways to interact with digital content, whether for entertainment, education, training, or professional applications.

One of the key advantages of immersive technologies is their ability to make complex digital interactions accessible to a wide range of users, including those who may not be familiar with traditional computer interfaces. For instance:

- In VR, users can navigate 3D spaces by simply walking and moving your body, leaning in, bending down, rather than learning complex keyboard and mouse controls.
- AR applications can overlay intuitive visual instructions onto real-world objects, making tasks like assembly or repair more straightforward for novices.
- Hand-based interactions can allow users to manipulate digital objects as if they were physical, reaching out to touch or grab, reducing the learning curve for 3D modeling or data visualization tasks.

Figure 1.2: VR users moving around freely in a larger space.

This natural interaction paradigm opens up new possibilities for digital content creation and consumption, potentially democratizing access to complex digital tools and experiences. As immersive technologies continue to evolve, they promise to make digital interactions more intuitive, engaging, and accessible to people of all backgrounds and technical skill levels.

1.2 The Evolution of Immersive Technologies

The journey of immersive technologies, particularly Virtual Reality (VR), spans several decades, with roots tracing back to the 1960s. This evolution has been marked by technological breakthroughs, changing applications, and an expanding vision of what's possible in virtual spaces.

1.2.1 Early Experiments

- **1960s**: Ivan Sutherland's "Sword of Damocles" laid the groundwork for modern VR systems. This early prototype, while bulky and limited, demonstrated the potential for head-mounted displays in creating immersive experiences.
- **1980s-1990s**: VR saw periods of hype and subsequent disillusionment as the technology struggled to meet expectations. Despite limitations in graphics and processing power, this era saw the development of many foundational concepts in VR.

1.2.2 Early Applications

For many years, VR remained primarily confined to specialized contexts.

Back when I first took a VR course in the late 1990s, VR was primarily used in expensive and specialized contexts—research laboratories and high-end simulators.

The main motivations for using VR traditionally were:

1. Training scenarios that are:
    - Expensive
    - Dangerous
    - Impossible to recreate in reality
2. Flight simulators
3. Prototyping
4. Visualization

Figure 1.3: Example of a flight simulator, one of the early applications of VR technology.

These early applications laid the groundwork for more widespread use of VR technology. For instance, the EasyADL project demonstrated how VR could be used for prototyping and testing scenarios that couldn't be replicated in reality due to sensor limitations.

In this project, I could create virtual sensors easily that would send information when the user grabbed something, when something left a cupboard, or when it was placed on the stove. I could easily create these virtual sensors to pass that information to the systems that were actually needed to implement the algorithms.

1.2.3 The Rise of Commercial VR

The modern era of commercial VR began to take shape in the mid-2010s, marking a significant shift that brought VR technology to a broader consumer audience. This period saw the development of more affordable and accessible VR hardware, setting the stage for widespread adoption.

1.2.4 Parallel Evolution of AR

While VR was developing, Augmented Reality (AR) was also making significant strides. The concept of overlaying digital information onto the real world began to gain traction, with early applications in heads-up displays for military aircraft and later in consumer mobile devices.

1.2.5 The Convergence of Technologies

As both VR and AR technologies advanced, the lines between them began to blur, giving rise to the concept of Mixed Reality (MR) and the broader field of Extended Reality (XR). This convergence has been driven by improvements in:

- Display technology
- Motion tracking
- Computer vision
- Processing power

These advancements have enabled more seamless blending of virtual and real-world elements, opening up new possibilities for immersive experiences. With recent hardware AR and MR is starting to catch up, but VR is still the more mature technology.

1.2.6 The Impact of Mobile Technology

The widespread adoption of smartphones and tablets has played a crucial role in the evolution of immersive technologies, particularly AR. The ubiquity of powerful, sensor-rich mobile devices has made AR experiences accessible to a wide audience, paving the way for applications in gaming, education, and various industries.

1.2.7 Looking Forward

The evolution of immersive technologies continues at a rapid pace, with ongoing developments in areas such as:

- Haptic feedback
- Eye tracking
- Brain-computer interfaces
- Volumetric displays

These advancements promise to further enhance the realism and interactivity of immersive experiences, potentially revolutionizing how we interact with digital content and each other in virtual spaces.

As we move forward, the challenge lies in harnessing these technologies to create meaningful, engaging, and accessible experiences that can benefit various aspects of human life, from entertainment and education to healthcare and professional training.

1.3 Understanding Presence and Immersion

Presence is a fundamental concept in immersive media, particularly in virtual reality (VR). It refers to the psychological state of feeling as if you are actually ("bodily") present in a virtual environment, despite knowing that you are not physically there.

1.3.1 Defining Presence

Michael Abrash, now chief science officer at Meta since initially working with VR at Valve, emphasized the importance of presence.

> Presence is: - Why we're excited - Unique to VR - The key to VR's success

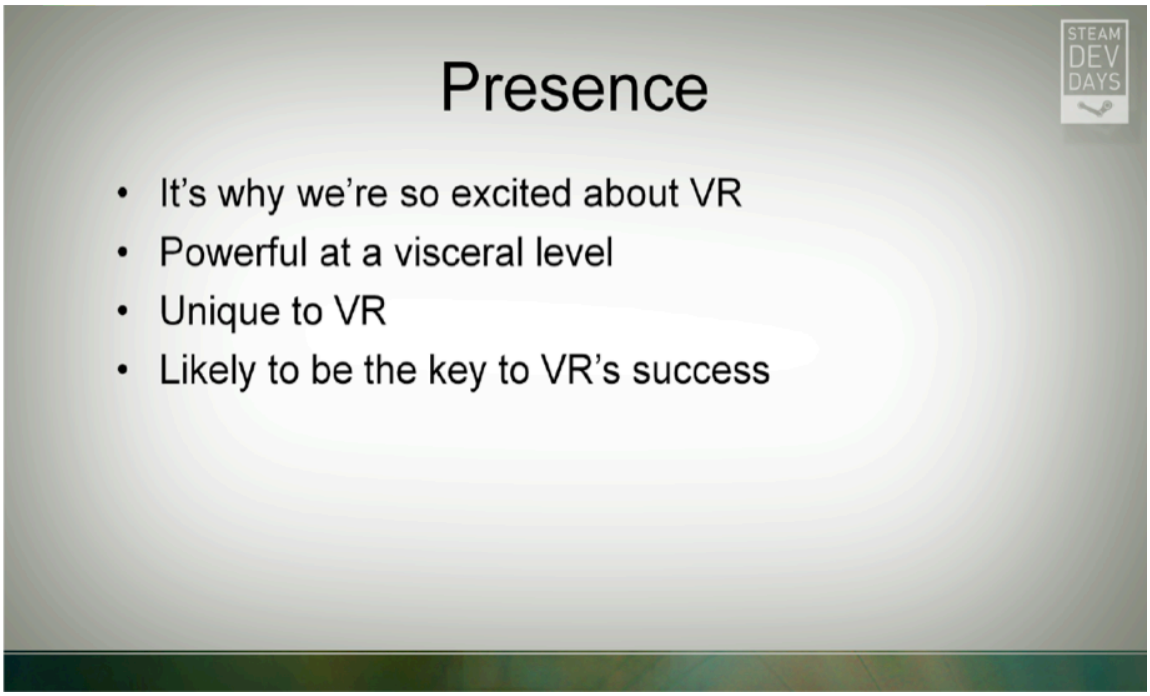


Figure 1.4: A slide from an early presentation on VR from Michael Abrash, then at Valve, now Chief Science Officer at Meta, on the importance of presence in VR. (Abrash 2014)

Presence is more than just visual immersion; it's about convincing the brain that the virtual environment is real.

As I've emphasized, the goal is to get the brain to work 'as if' in a real environment.

1.3.2 The Power of Presence

When presence is achieved, users may react to virtual stimuli as if they were real.

At one time, I was testing a VR environment for several hours, lifting containers and pouring virtual liquids from one to another. I'd been seated at a virtual table, completely absorbed in the task. When my hands grew tired, I instinctively tried to rest them on the virtual table surface.

My hands passed straight through, and I felt a genuine chill down my spine. This reaction showed how thoroughly my brain had accepted the virtual environment as real—even knowing it was virtual couldn't prevent the instinctive response.

This anecdote illustrates how powerful the sense of presence can be, causing instinctive reactions to virtual objects.

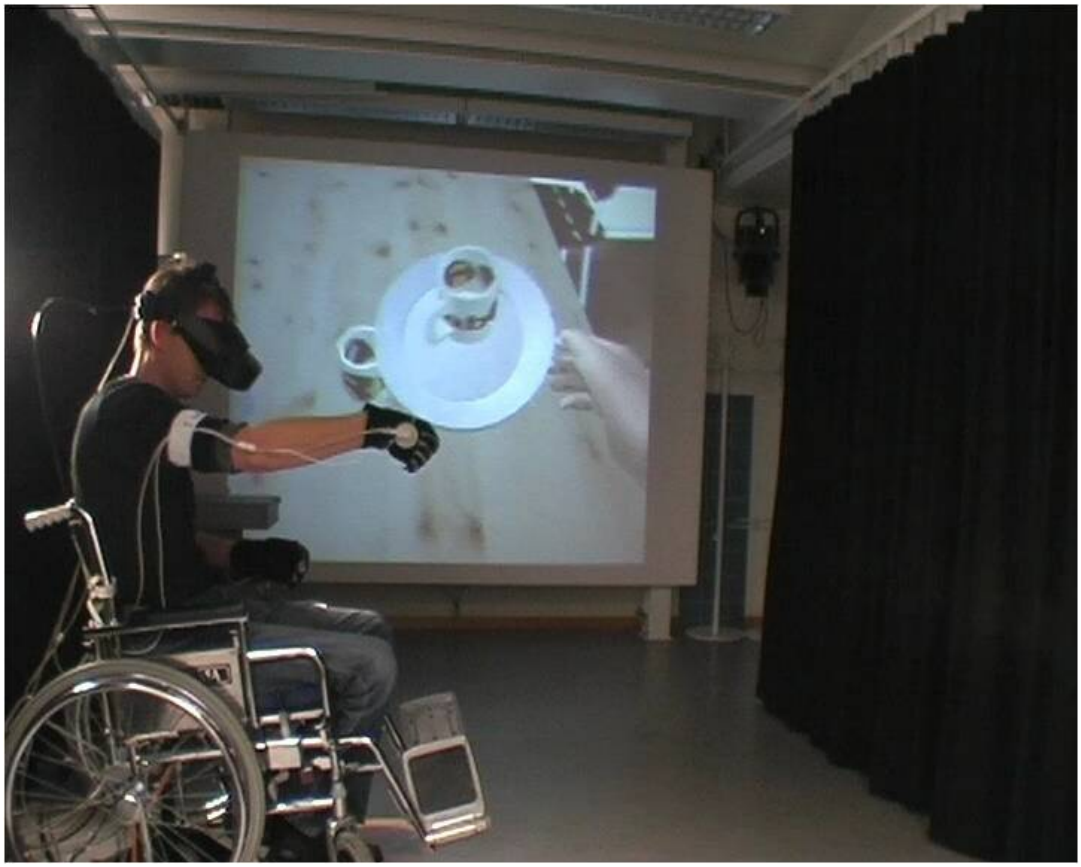


Figure 1.5: Examples of users interacting with virtual objects as if they were real.

1.3.3 Factors Contributing to Presence

Several factors contribute to creating a sense of presence. The most important are:

1. **Interaction**: The ability to interact with the virtual environment in natural, intuitive ways strengthens the sense of presence.
2. **Consistency**: The virtual world must behave consistently and predictably to maintain the illusion of reality.
3. **Body Ownership**: Seeing a virtual representation of your body that moves as you do can significantly enhance presence.

These can also contribute significantly, but are not as critical:

1. **Visual Fidelity**: High-resolution displays and realistic graphics help convince the brain of the environment's reality.
2. **Audio**: Spatial audio that accurately represents the virtual space enhances immersion.

1.3.4 The McGurk effect

The McGurk effect is a perceptual phenomenon that demonstrates how our brains integrate visual and auditory information to create a coherent perception of speech. This effect is crucial for understanding how presence is created in VR environments.

In the McGurk effect:

1. A person is shown a video of someone saying one sound (e.g., "ga-ga")
2. The audio is replaced with a different sound (e.g., "ba-ba")
3. The viewer often perceives a third, intermediate sound (e.g., "da-da")

This illusion occurs because the brain attempts to reconcile the conflicting visual and auditory information, resulting in a perception that matches neither the visual nor the auditory input alone.

YouTube Video

The McGurk Effect - Auditory Visual Illusion
This classic psychological demonstration shows how our brain processes conflicting visual and auditory information. In the video, you'll see a person saying one sound while hearing a different sound, yet perceiving a third, intermediate sound. This illusion is particularly relevant to VR because it persists even when you're aware of it, demonstrating how our perception can be reliably manipulated through coordinated sensory inputs.
Watch at: https://www.youtube.com/watch?v=2k8fHR9jKVM&t=s

What makes the McGurk effect particularly relevant to VR is its persistence even when the viewer is aware of the illusion.

This is a kind of illusion that is not dependent on you being aware of it. It works even though you know about it.

This demonstrates how our perceptual systems can be influenced by multisensory input, even overriding our conscious knowledge. In VR, this principle is leveraged to create a

sense of presence by providing coherent multisensory experiences that our brains interpret as real, even when we know we're in a virtual environment.

1.3.5 Understanding Different Types of Immersion

Immersion in virtual reality can be understood in two distinct but complementary ways: technological immersion and narrative immersion. Both contribute to the overall sense of presence in virtual environments but operate through different mechanisms.

1.3.5.1 Technological Immersion

Technological immersion refers to the degree to which our senses are enveloped by the virtual environment. This form of immersion is primarily achieved through hardware and software capabilities that block out the physical world and replace it with virtual stimuli. Key aspects include:

1. Visual coverage (field of view)
2. Audio spatialization
3. Haptic feedback
4. Motion tracking accuracy

The more complete this sensory replacement, the higher the level of technological immersion.

1.3.5.2 Narrative Immersion

While technological immersion focuses on sensory engagement, narrative immersion relates to our psychological engagement with the virtual environment's story, context, and unfolding events. This type of immersion can occur even with relatively simple technology if the narrative elements are compelling.

As you explore these kinds of environments, they build up stories and narratives, which fit very well with how we generally remember things and understand the world.

The interplay between these two types of immersion can create powerful experiences in virtual environments. Later chapters will explore how narrative immersion can be particularly effective in visualization and educational applications, where engagement with content often matters more than technological sophistication.

1.3.6 The Future of Presence and Immersion

As VR technology continues to advance, we can expect even more convincing experiences of presence. Future developments may include:

- Improved haptic feedback for more realistic touch sensations
- Advanced eye-tracking for more natural visual experiences
- Brain-computer interfaces for direct neural engagement

Understanding and enhancing presence and immersion remain central goals in the development of immersive technologies, driving innovation in hardware, software, and content creation.

1.4 Avatars and Virtual Embodiment

Virtual avatars and the concept of embodiment play crucial roles in immersive experiences, particularly in virtual reality (VR). They significantly impact how users perceive themselves and interact within virtual environments. This section explores the foundational psychological principles underlying virtual embodiment, while practical implementations and technical avatar creation systems are covered in Section 5.9.

1.4.1 The Rubber Hand Illusion

The concept of embodiment in virtual reality is closely related to the psychological phenomenon known as the rubber hand illusion. This illusion, first demonstrated by Botvinick and Cohen in 1998, shows how easily our brains can be tricked into accepting an artificial limb as part of our body.

In the classic rubber hand experiment: 1. A participant's real hand is hidden from view. 2. A rubber hand is placed in a visible position. 3. Both the real hand and the rubber hand are stroked simultaneously with a brush. 4. After a short time, many participants begin to feel as if the rubber hand is their own.

YouTube Video

Rubber Hand Illusion Experiment
This classic psychological experiment demonstrates how easily our brains can be tricked into accepting an artificial limb as part of our body. The video shows the experimental setup where participants' real hands are hidden while they observe a rubber hand being stroked simultaneously with their hidden hand. This illusion forms the foundation for understanding virtual embodiment in VR environments, showing how coordinated visual and tactile stimuli can manipulate our sense of body ownership.
Watch at: https://www.youtube.com/watch?v=sxwn1w7MJvk&t=30s

This illusion demonstrates the brain's remarkable plasticity in constructing our sense of body ownership. It reveals that our perception of our body is not fixed, but can be manipulated through coordinated visual and tactile stimuli.

In VR, this effect is leveraged to create a sense of ownership over virtual body parts or entire avatars. When users see virtual hands moving in sync with their real hand movements, they quickly begin to feel as if those virtual hands are their own. This principle extends beyond just hands - entire virtual bodies can be embodied in VR, leading to powerful immersive experiences. ### The Illusion of Body Ownership

Research conducted at the Karolinska Institute's Brain, Body and Self Laboratory (Group Ehrsson) has demonstrated how easily our brains can be tricked into accepting a virtual or artificial body as our own. This phenomenon is closely related to the sense of presence in VR environments.

A striking example comes from an experiment where a participant wearing a VR headset had a strong reaction when a knife was brought near their virtual body.

> - I viewed the manikins body as being my body. - Then researchers slid a knife across the dummy's body. - You have the reaction, because she's not, it's not like she's trying to stab me with it, but you do have the reaction to just sort of pull away a little bit because she, I mean, it really seems like she's about to put something sharp against my stomach.
>
> - *Quote from video*

This visceral response occurs even though the participant is consciously aware they are looking at a mannequin body through a VR headset.

YouTube Video

Body Ownership Illusion in VR
This video demonstrates how VR can create powerful illusions of body ownership, showing participants' visceral reactions to virtual bodies being threatened or touched. The demonstration reveals how quickly our brains can accept virtual bodies as our own, even when we're consciously aware we're looking at a mannequin through a VR headset. This research forms the basis for understanding avatar embodiment in virtual environments.
Watch at: https://www.youtube.com/watch?v=rawY2VzN4-c&t=s

1.4.2 Flexibility of Body Perception

Our perception of our own body is surprisingly flexible and can be manipulated in VR environments. A study titled "Being Barbie: The Size of One's Own Body Determines the Perceived Size of the World" demonstrated how inhabiting different sized virtual bodies can alter our perception of the world around us.

In this study, participants were asked to estimate how big a cube was. You can see that they were now using their doll bodies as reference points when showing with their own hands how big the cube was. The actual cube, of course, was not that big.

This flexibility extends beyond just size. Researchers have experimented with altering various aspects of virtual bodies, including:

- Body shape
- Sex
- Race

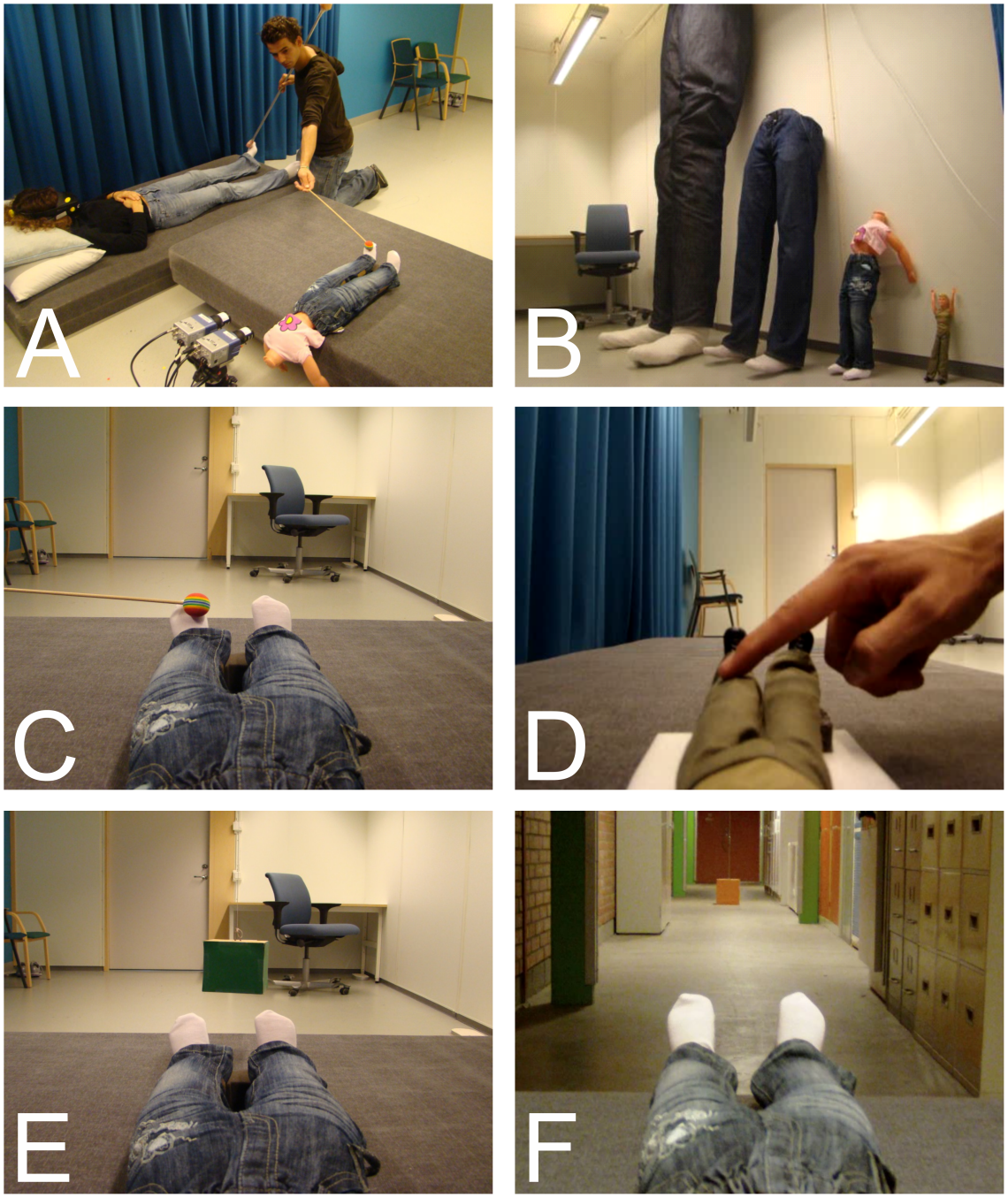


Figure 1.6: Participants estimating object sizes while embodying different sized avatars.

1.4.3 Psychological Impact of Avatar Embodiment

The way we perceive our virtual bodies can have profound effects on our psychology and behavior. A study by Peck et al. (2013) explored how embodying an avatar with dark skin color could affect implicit racial bias.

If you get this experience of being in a virtual reality environment and having a darkly colored body, then that affects how much racial bias you have when evaluated before and after the experience.


Putting yourself in the skin of a black avatar reduces implicit racial bias

Tabitha C. Peck [a], Sofia Seinfeld [a,b], Salvatore M. Aglioti [c], Mel Slater [a,d,e,*]

Figure 1.7: Study on embodying avatars of different races.

The implications of this research extend far beyond just racial attitudes.

Depending on how you perceive yourself, you might even become better at math, for instance. This can really affect how you see the world, what you believe yourself to be able to do, and what judgments you are making.

1.4.3.1 The Proteus Effect

The Proteus Effect demonstrates how users may alter their behavior to conform to expectations set by their avatar's appearance. For example, users with taller avatars may negotiate more aggressively in virtual environments.

1.4.4 Implications for VR Design

Understanding the rubber hand illusion and its extensions in VR has significant implications for VR design:

1. Avatar Design: Avatars that move in sync with user movements enhance the sense of embodiment.
2. Interaction Design: Designing interactions that reinforce the connection between user actions and avatar responses can strengthen the illusion of body ownership.
3. Emotional Responses: Designers can leverage this illusion to create more emotionally impactful experiences, as users may react to virtual stimuli as if they were real.

4. Therapeutic Applications: The body ownership illusion in VR has potential applications in therapy, such as treating phantom limb pain or body dysmorphia.

Ethical Considerations: The power to manipulate users' sense of body ownership and self-perception carries significant ethical responsibilities. Research showing that virtual embodiment can influence implicit bias, cognitive performance, and self-concept demonstrates both the potential and the risks of these technologies. Questions of psychological safety, age-appropriate design, and the long-term impacts of virtual embodiment require careful consideration. We explore these ethical implications in depth in Chapter 10, examining how developers can create transformative experiences while respecting user wellbeing and autonomy.

By understanding and leveraging these principles, VR designers can create more immersive, engaging, and potentially transformative experiences. The rubber hand illusion and its VR extensions demonstrate the power of our brains to adapt to new body schemas, opening up exciting possibilities for virtual embodiment and presence in digital worlds.

1.4.5 Future Directions

As VR technology advances, we can expect more sophisticated avatar systems that provide even more convincing experiences of embodiment. This could lead to applications in:

- Therapy and mental health treatment
- Education and skill training
- Social interaction and collaboration in virtual spaces

The study of avatars and virtual embodiment remains a rich area for research, with potential implications for our understanding of consciousness, self-perception, and social interaction.

For those interested in exploring this topic further, the Brain, Body and Self Laboratory publications page offers a wealth of research papers on related experiments and findings.

1.5 The Future of Immersive Technology

As immersive technologies continue to evolve at a rapid pace, the future of this field promises exciting developments and widespread impact across various sectors. This section explores potential advancements and implications for the future of immersive media.

1.5.1 General Trends

1. **Increased Accessibility**: As hardware becomes more affordable and user-friendly, immersive technologies will likely become more accessible to a wider audience.
2. **Enhanced Realism**: Advancements in display technology, haptics, and sensory feedback systems will contribute to increasingly realistic and immersive experiences.
3. **Seamless Integration**: The lines between physical and digital realities will continue to blur, with AR and MR technologies becoming more integrated into our daily lives.
4. **AI Integration**: Artificial intelligence will play a larger role in creating dynamic, responsive immersive environments (see Chapter 8 for comprehensive coverage).
5. **Social VR**: As virtual social interactions become more sophisticated, we may see new forms of communication and collaboration emerge.

1.5.2 Potential Applications

While detailed discussions of applications will be covered in later chapters, some key areas of interest for future immersive technology include:

- Education and Training
- Healthcare and Therapy
- Design and Engineering
- Entertainment and Gaming
- Remote Work and Collaboration
- Tourism and Cultural Experiences

1.5.3 Challenges and Considerations

As immersive technologies become more prevalent, several challenges will need to be addressed:

1. **Privacy and Data Security**: Ensuring the protection of personal data in increasingly connected immersive environments.
2. **Ethical Implications**: Addressing the psychological effects of prolonged immersion and the potential for manipulation in virtual environments.
3. **Accessibility**: Ensuring that immersive technologies are inclusive and accessible to all, including those with disabilities.

4. **Content Creation**: Developing tools and platforms that allow for efficient creation of high-quality immersive content.

1.5.4 Skills and Opportunities

The growing importance of immersive technologies is creating new career opportunities across various fields. As the technology evolves, there will be an increasing demand for professionals skilled in:

- Immersive experience design
- 3D modeling and animation
- Spatial computing
- XR development
- Immersive storytelling

1.5.5 Conclusion

The future of immersive media is bright and full of potential. As these technologies continue to advance and integrate more seamlessly into our lives, they have the power to transform how we work, learn, entertain ourselves, and interact with the world around us. While challenges remain, the opportunities for innovation and positive impact are vast.

Note: Detailed discussions of hardware evolution and specific applications will be covered in subsequent chapters of this compendium.

1.6 Further Reading

Chapter 1 introduced the fundamental concepts of immersive media, including virtual reality (VR), augmented reality (AR), and mixed reality (MR). We explored the importance of presence and immersion in creating compelling XR experiences, and discussed the potential applications of these technologies across various fields. To deepen your understanding of these foundational concepts and their implications, consider the following resources:

1.6.1 Research Papers

- Sjölie, D., & Badylak, S. (2019). Mind tricks for presence. In Proceedings of the 14th International Conference on the Foundations of Digital Games (FDG '19). Association for Computing Machinery, New York, NY, USA, Article 47, 1–7.
  - This paper introduces concepts of synchronized reality and grounded simulation as starting points for designing mixed reality systems with optimal presence, providing case studies of commercial VR applications.
- Sjölie, D. (2012). Presence and general principles of brain function. Interacting with Computers, 24(4), 193-202.
  - This paper explores the relationship between presence in virtual environments and general principles of brain function, providing foundational insights into the cognitive aspects of immersive experiences.
- Slater, M. (2009). Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1535), 3549-3557.
  - This paper introduces the concepts of place illusion and plausibility illusion as key components of presence in virtual environments, explaining how these factors can lead to realistic behavior in immersive VR.
- Sanchez-Vives, M. V., & Slater, M. (2005). From presence to consciousness through virtual reality. Nature Reviews Neuroscience, 6(4), 332-339. This paper provides an overview of presence in virtual reality and its relationship to consciousness.
  - This review paper explores the concept of presence in immersive virtual environments, discussing how the sense of "being there" is signaled by people acting and responding realistically to virtual situations and events, and its relationship to consciousness.

2 XR Technologies and the Reality-Virtuality Continuum

2.1 The Reality-Virtuality Continuum

The reality-virtuality continuum is a conceptual framework that describes the full spectrum of experiences ranging from the completely real to the fully virtual. This continuum provides a basis for understanding different types of mixed reality experiences and how they blend elements of the physical and digital worlds.

2.1.1 Understanding the Continuum

At one end of the spectrum lies our familiar physical reality - the tangible world we interact with daily. On the opposite end, we find fully immersive virtual environments, such as fantastical realms like the Lord of the Rings universe. Between these extremes, there exists a range of mixed reality experiences:

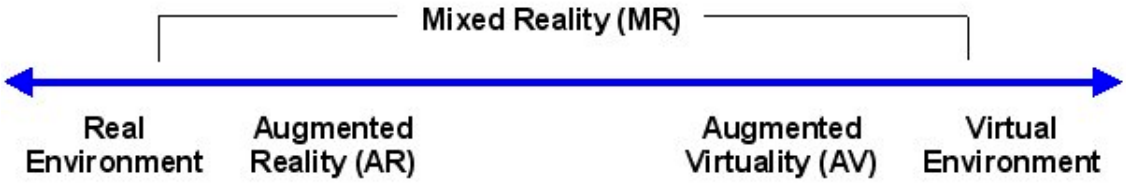


Figure 2.1: Virtuality Continuum

I find it helpful to think about the spectrum in terms of mixing approaches. At the augmented reality end, you still feel essentially present in your physical reality, but you can add digital and virtual elements to that world. At the other end, you can feel like you're on a virtual moon base—something completely removed from your actual physical reality—but where you can still add elements from the real world, such as your physical desk or a view of someone else in the room.

Key concepts mapped onto the spectrum are:

1. **Real Reality (RR)**: Your everyday, familiar, physical environment.
2. **Augmented Reality (AR)**: Closer to the physical reality end, AR enhances our perception of the real world by overlaying digital information or objects onto it. For example, a user might see virtual navigation arrows overlaid on real city streets. Users can interact with virtual elements while still feeling present in and aware of their physical surroundings.
3. **Mixed Reality (MR)**: Can include everything between RR to VR, with all possible mixings of the real and the virtual. In the central part of the continuum, MR creates environments where physical and digital objects coexist and interact in real time. E.g., a virtual character that can interact with real-world objects in your living room, an ordinary table turning into an interactive touch display surface or the view out through a window changing to a view onto Mars.
4. **Augmented Virtuality (AV)**: Augmenting your virtual world with elements from physical reality. E.g., bringing real people from your physical surroundings into your personal virtual office. Or making sure you can see and use your physical mouse and keyboard while in VR. Mostly an academic concept, not used much in the industry.
5. **Virtual Reality (VR)**: At the far end of the continuum, VR immerses users in a completely synthetic environment. This could be as fantastical as exploring a virtual Hogwarts castle or as practical as a fully simulated surgical training environment. Allows for full-body interaction in a digital space. Unlimited by the physical space, although care is required when moving around (navigating) in VR.

The reality-virtuality continuum is not a rigid classification but rather a fluid spectrum. Many experiences blur the lines between these categories. For instance, a virtual moon base experience might incorporate a view of your real-world desk, creating a hybrid environment that combines elements from different points on the continuum.

Understanding this continuum is crucial for conceptualizing how different technologies can blend the physical and digital worlds. It opens up new possibilities for creating immersive experiences that can range from subtle augmentations of our physical reality to complete transportation into virtual worlds, with countless variations in between.

As we explore each category in more depth in the following sections, we'll examine how different technologies and applications leverage various points along this continuum to create unique and engaging experiences.

2.2 Virtual Reality (VR) Systems

Virtual Reality (VR) systems represent the fully immersive end of the reality-virtuality continuum, providing users with complete digital environments that replace their physical surroundings. This section explores the components, capabilities, and evolution of modern VR systems.

2.2.1 Key Components of VR Systems

Modern VR systems typically consist of several key components:

1. **Head-Mounted Display (HMD)**: The primary interface between the user and the virtual world.
2. **Motion Controllers**: Allow users to interact with the virtual environment.
3. **Tracking System**: Monitors the user's movements and position in space.
4. **Computer or Console**: Generates the virtual environment and processes user interactions.

2.2.2 Brief History of VR

While VR has seen a significant resurgence in recent years, its roots trace back to the 1960s. For decades, VR remained primarily confined to specialized contexts.

The basic motivations for using VR remain fundamentally the same as when I first took a VR course in the late 1990s: training scenarios where it's expensive, dangerous, or impossible to practice in reality. This core principle has remained consistent even as the technology has advanced dramatically.

Early applications included flight simulators, military training, and scientific visualization. However, limitations in technology and high costs restricted widespread adoption.

2.2.3 The Modern Era of VR (2016 onwards)

The modern era of commercial VR began in 2016 with the release of several key headsets:

1. HTC Vive: Developed by Valve and manufactured by HTC
2. Oculus Rift: The first version from Oculus, now owned by Facebook
3. Microsoft's Windows Mixed Reality headsets: A cheaper alternative
4. Mobile VR solutions: Samsung Gear VR and Google Daydream
5. PlayStation VR: Sony's offering for the PlayStation console

(a) HTC Vive (b) Oculus Rift

Figure 2.2: The first consumer oriented VR headsets, from 2016, HTC Vive and Oculus Rift.

Image Attribution: - HTC Vive: "CES2016_HTCVive_Pre_Winters" by ETC-USC is licensed under CC BY 2.0 - Oculus Rift: Image by KniBaron from Bangkok, Thailand, licensed under CC BY 2.0

These headsets ranged in price from around 4,000 to 10,000 crowns. The mobile VR solutions, while innovative, have largely been discontinued due to the friction involved in using a smartphone as the display.

2.2.4 Recent Developments in XR Hardware

The XR landscape has continued to evolve rapidly:

1. **Meta Quest 3(S)**: A fully mobile, standalone headset that offers 6DoF (six degrees of freedom) tracking without the need for external sensors or a connected PC. The Quest 3 is the better version with advanced optics and comfort, while Quest 3S is the newest, using the same chip and capable of running the same applications but otherwise optimized to be as cheap as possible.
2. **Valve Index**: Developed as a high-end PC-connected headset focusing on wide field of view, comfort, sounds and advanced controller design. The Valve Index is one of the older headsets still in use, as few newer headsets are developed specifically for PC-desktop-VR.
3. **Bigscreen Beyond 2**: A 107 g, custom-fit SteamVR headset with built-in eye tracking and optional comfort kits for longer sessions.(Bigscreen, Inc. 2024) Like the original Beyond, it relies on external base stations and controllers, but the new model

shows how aggressively PCVR rigs can shrink when every gram is optimized around a single wearer's face.

4. **Pico 4**: The most direct competitor to Meta Quest 3(S), with similar features. Also standalone. Includes enterprise versions with eye tracking etc.
5. **Samsung Galaxy XR ("Project Moohan")**: Samsung's first Android XR headset blends 4K-per-eye micro-OLED displays, Snapdragon XR2+ Gen 2 compute, and comprehensive inside-out tracking while leaning on Google's Android XR stack for software continuity across phones, tablets, and wearables.(West 2025)
6. **Apple Vision Pro**: A "prosumer", early-adpoter, headset from Apple, providing high quality visuals and mixed reality with hand and eye tracking for a hefty price.
7. **Varjo XR-4**: An ultra-high-resolution headset aimed at professional applications, includes mixed reality with professional hand and eye tracking.
8. **Meta Ray-Ban Display + Neural Band**: Lightweight smart glasses with a monocular HUD paired with an sEMG wristband for precise text input, showcasing how glasses-class wearables are adopting richer interactions typically found in headsets.(Meta Platforms 2024)

2.2.5 The Form-Factor Spectrum (2025)

To understand how these devices relate to one another, it helps to visualize them along a spectrum that runs from fully tethered PCVR rigs to lightweight smart glasses. Each rung of the spectrum balances compute location, interaction methods, and ergonomics differently.

Segment	Representative Hardware	Primary Compute	Core Interactions	Typical Use Cases
PCVR	Valve Index, **Bigscreen Beyond 2** (107 g custom-fit)(Bigscreen, Inc. 2024)	External PC with discrete GPU	Controllers with precise SteamVR tracking, optional finger sensing	Simulation labs, enthusiasts seeking fidelity
Performance Standalone	Meta Quest 3/3S, Pico 4	On-headset mobile SoC	Controllers, hand tracking, mixed reality passthrough	Consumer gaming, productivity MR

Segment	Representative Hardware	Primary Compute	Core Interactions	Typical Use Cases
Premium Standalone MR	Apple Vision Pro, Samsung Galaxy XR	On-headset mobile SoC with co-processors	Eye and hand tracking, voice, spatial video passthrough	Prosumer productivity, enterprise collaboration
Split Compute / Tethered Ultra-light	Meta's reported ultralight headset + compute puck	Waist or pocket compute puck	Eye tracking with gaze-and-pinch, sEMG bands	Long-session media viewing, travel-ready VR
Smart Glasses & HUD	Meta Ray-Ban Display + Neural Band, Samsung/-Google HUD glasses	Paired phone/cloud	Wrist-based sEMG, voice, subtle gestures	Assisted reality, navigation, AI companions

The newest announcements are compressing weight and thermal budgets without giving up expressiveness. Meta's reported ultralight puck-based headset aims to deliver sub-110 gram eyewear with gaze-and-pinch as the primary modality, while Bigscreen Beyond 2 demonstrates how far miniaturized optics and custom fitting can push PCVR hardware.(Heaney 2024; Bigscreen, Inc. 2024) Samsung's Galaxy XR shows how manufacturers are pairing high-end micro-OLED optics with Android XR to compete head-on with Apple's Vision Pro in the standalone MR tier, while Google positions Gemini-powered Android XR services as the connective AI tissue across both the headset and future eyewear.(West 2025; Google LLC 2024b, 2024a) On the glasses end of the spectrum, Meta's Ray-Ban Display (69 g) pairs a monocular HUD with the Neural Band sEMG wristband for precise finger-driven text input, signaling that lightweight devices can still support fine-grained control.(Meta Platforms 2024)

i Android XR as a cross-device layer

Google's 2025 Android XR announcement frames a single software stack that spans headsets and glasses, with Gemini multimodal AI handling perception, assistant behavior, and cross-device continuity.(Google LLC 2024b, 2024a) Treat Android XR as connective tissue between the spectrum segments: developers can target one platform while deploying to puck-driven headsets, standalone devices, or future smart glasses, tapping Gemini for scene understanding, translation, and generative overlays.

2.2.5.1 Smart-Glasses Market Snapshot

- **Display strategies**: Meta opts for a high-brightness monocular HUD in Ray-Ban Display, while Samsung and Google preview a waveguide HUD slated for a 2026 launch to complement their Android XR headset push.(Meta Platforms 2024; Heaney 2025)
- **Input diversity**: sEMG wristbands, gaze-and-pinch, and always-listening voice agents are emerging to replace touchpad-only interaction.
- **Battery and thermals**: 6-hour eyewear runtimes and IP-rated accessories hint at expectations for all-day wear, but compute still regularly offloads to phones or pucks.
- **Ecosystem bets**: Meta ties hardware to Meta AI services, while Google positions Android XR as the open alternative, weaving Gemini agents into Samsung's hardware roadmap and the broader Android developer base.(Meta Platforms 2024; Google LLC 2024b, 2024a; Heaney 2025)

The spectrum perspective helps frame design decisions in later chapters: interaction designers can map capabilities to expected hardware constraints, while developers can plan how features degrade gracefully across different compute locations.

Figure 2.3: Varjo VR-1

Prices start around 4,000 SEK for the Meta Quest 3S, with different configurations of consumer headsets up to around 10,000 SEK. Apple Vision Pro is not yet available in Sweden but costs 4,000 EUR elsewhere in Europe. The Varjo XR-3, aimed at professional users, is even more expensive.

Professional-Grade Hardware

Varjo, a Finnish company, produces exceptionally impressive high-end virtual reality headsets. While these systems cost 50,000 SEK and above—sometimes reaching over 100,000 SEK—they offer exceptionally high resolution that enables users to see fine details in virtual environments that would be impossible with consumer-grade hardware.

There are more options out there, including HTC who where the first to release consumer VR and are still in the game but not as popular these days.

2.2.6 Key Technical Aspects

2.2.6.1 Field of View (FOV)

Field of View refers to the extent of the observable environment at any given time. It's typically measured in degrees:

- Most consumer VR headsets offer an FOV between 90 and 110 degrees.
- Some high-end or experimental designs push this further but it has not really taken hold.
- Some high-end or experimental designs push this further but it has not really taken hold.

  I know how much ya'll love field-of-view and want more. I'm with you. I like it. I get it, I do. The tradeoffs are so bad. The tradeoffs on weight, form factor, compute, thermals… it's all bad,

  - *Quote from Meta CTO Andrew Bosworth*

Meta Explains Why It Sees Wide Field-of-View Headsets as a 'bad tradeoff'

2.2.6.2 Resolution

Higher resolution displays provide clearer, more detailed images, enhancing realism and reducing the "screen door effect". Modern high-end headsets offer resolutions exceeding 2000x2000 pixels per eye.

2.2.6.3 Tracking and Degrees of Freedom

- **3DoF (3 Degrees of Freedom)**: Only tracks rotational movement (looking left-/right, up/down, and tilting head)
  - This was somewhat common in the cheapest headsets in the beginning of commercial VR, but is now completely outdated.
- **6DoF (6 Degrees of Freedom)**: Tracks both rotational and positional movement (including moving forward/backward, left/right, and up/down)

There are two main approaches to tracking in VR:

1. **Inside-out tracking**:

- Cameras on the HMD look out into the world
- More portable and easier to set up in new locations
- This is the dominating approach with recent headsets like the Meta Quest 3(S) and the Apple Vision Pro.

2. **Outside-in tracking**:

   - Cameras or sensors in the room track the user
   - Requires more setup but can be more precise
   - Headsets using versions of this tracking include Valve Index and Bigscreen Beyond.

2.2.7 Conclusion

VR systems have evolved dramatically in recent years, becoming more accessible, powerful, and versatile. From high-end professional systems to consumer-friendly standalone headsets, VR technology is finding applications in diverse fields such as entertainment, education, training, and professional visualization. As these systems continue to advance, we can expect even more immersive and realistic virtual experiences in the future.

2.3 Augmented Reality (AR) Technologies

AR technology overlays digital content onto our view of the real world, enhancing our perception and interaction with our surroundings. This section explores the devices, software, and applications that make AR possible, focusing on current technologies and their applications.

2.3.1 Types of AR Systems

AR systems can be broadly categorized into three types:

1. **Mobile AR**: Uses smartphones or tablets as the AR device.
2. **Head-Mounted Displays (HMDs)**: Wearable devices that provide a see-through display.
3. **Projection-based AR**: Projects digital information directly onto physical objects or surfaces.

2.3.2 Mobile Augmented Reality

Mobile AR is currently the most accessible and widely used form of AR technology. Major tech companies like Google and Apple have released development toolkits (ARCore and ARKit respectively) that enable AR experiences on smartphones. More recently companies such as Snapchat and Niantic has made significant plays at AR.

YouTube Video

Mobile AR Demonstration - Real-time Object Placement
This demonstration showcases the core capabilities of mobile augmented reality using smartphones. Viewers will see how AR applications can detect surfaces and place virtual objects in real-world environments, illustrating the fundamental tracking and rendering technologies that make mobile AR possible. The video demonstrates the accessibility of AR technology that most viewers can experience on their own devices today.
Watch at: https://www.youtube.com/watch?v=xCdjIDnCtps&t=s

Most smartphones today have the capability to run mobile AR applications where you can view the camera feed and add virtual content to the real world. This technology has become remarkably accessible, with most users having these capabilities right in their pocket.

Mobile AR applications typically use the device's camera to view the real world and then overlay digital content onto this view. This technology has found applications in various fields, including:

1. Gaming (e.g., Pokémon Go)
2. Navigation and wayfinding
3. Education and training
4. Marketing and advertising

2.3.3 Advanced AR: HoloLens and Beyond

Moving beyond mobile AR, we encounter more sophisticated AR devices like Microsoft's HoloLens. These devices offer a more immersive and hands-free AR experience.

YouTube Video

Microsoft HoloLens AR Demonstration - Spatial Computing
This video demonstrates Microsoft's HoloLens capabilities, showing advanced AR features including spatial mapping, gesture-based interaction, and see-through holographic displays. Viewers will observe how the HoloLens creates immersive mixed reality experiences with 3D holograms that appear to interact with the physical environment, highlighting both the potential and current limitations of head-mounted AR displays, including the restricted field of view that constrains where virtual content can appear.
Watch at: https://www.youtube.com/watch?v=cvLdbpICVGk&t=s

Key features of advanced AR headsets include:

1. See-through displays
2. Spatial mapping and understanding
3. Natural gesture-based interactions
4. Voice commands

However, current limitations include a restricted field of view for virtual content.

Current AR headsets face significant field of view limitations. In many demonstrations, you can see that virtual augmentations are only visible within a restricted rectangular area in the center of the user's vision, rather than across their full field of view.

2.3.4 Industrial Augmented Reality

One of the most promising applications of AR technology is in industrial settings. Industrial applications represent one area where AR technology can be genuinely useful with current capabilities. This practical utility explains why Microsoft focused their later HoloLens releases on enterprise markets rather than consumer sales.

YouTube Video

Industrial AR Application - Manufacturing and Assembly
This video showcases practical industrial applications of augmented reality in manufacturing and assembly environments. Viewers will see how AR technology provides real-time guidance and information overlay for workers, demonstrating assembly instructions, quality control procedures, and maintenance protocols. The demonstration illustrates why Microsoft focused HoloLens development on enterprise applications, showing how AR can improve efficiency, reduce errors, and enhance worker safety in industrial settings where the technology provides immediate practical value.
Watch at: https://www.youtube.com/watch?v=m16XwuYfAGo&t=s

Industrial AR applications include:

1. Assembly line assistance
2. Maintenance and repair guidance
3. Quality control
4. Training and skill development

These applications can significantly improve efficiency, reduce errors, and enhance worker safety in various industrial settings.

2.3.5 Recent Developments in AR

The AR hardware landscape has seen significant advancements in 2024, with major tech companies pushing the boundaries of what's possible in wearable AR devices. However, we have also seen Microsoft discontinuing the Hololens line of products, as they seem to increasingly focus on software in the XR space.

2.3.5.1 Meta Orion

Meta's Orion AR glasses prototype, showcased in September 2024, represents a significant leap forward in AR technology. Key features include:

- 70-degree field of view, substantially wider than competitors
- Advanced silicon-carbide lenses and micro LED projectors
- Resolution of 13 pixels per degree (with plans to increase to 26)
- Full sensor suite including:
  - Eye tracking
  - Hand tracking

  - Room tracking cameras

- Wireless neural wristband for input
- Separate wireless processor puck for computing
- Capability to display multiple apps simultaneously
- AI integration for enhanced experiences

Please note that while Orion shows impressive technical achievements, it remains a prototype focused on development and testing rather than consumer release.

2.3.5.2 Snap Spectacles (5th Generation)

Snap's latest iteration of AR glasses, released in September 2024, offers:

- 47-degree field of view
- Gesture control capabilities
- AR effects and entertainment features
- Developer-focused distribution ($99/month developer kit)
- More robust but bulkier design compared to previous versions

While more limited in capabilities compared to Meta's Orion, Snap's approach focuses on practical, entertainment-oriented AR applications.

2.3.5.3 Future Outlook

As AR technology continues to mature, we're seeing a trend toward: - Smaller, more efficient form factors - Enhanced display technologies - More sophisticated input methods - Stronger integration with AI and spatial computing

While true consumer AR glasses may still be several years away, recent developments from companies like Meta and Snap demonstrate significant progress toward making immersive AR a practical reality.

Meta's Ray-Ban smart glasses, while not offering AR display capabilities, hint at another potential track toward mainstream adoption. By focusing on a fashionable form factor and integrating AI-powered voice commands and camera features, these glasses demonstrate how companies might bridge the gap between current technology limitations and consumer expectations. This "walk before you run" approach of creating socially acceptable smart glasses could help pave the way for eventual AR integration once display technology catches up with our ambitions for all-day wearable AR. The success or failure of such interim products may provide valuable insights into how AR glasses will need to evolve to achieve widespread adoption.

2.3.6 The Future of AR: Towards Ubiquitous Computing

Industry leaders like Mark Zuckerberg envision a future where AR becomes an integral part of our daily lives. The goal is to develop unobtrusive AR devices that look and feel like normal glasses or even contact lenses.

YouTube Video

Mark Zuckerberg on the Future of Augmented Reality
In this presentation, Meta's CEO Mark Zuckerberg outlines his vision for the future of augmented reality and its potential to transform daily life. Viewers will hear about the long-term goal of creating unobtrusive AR devices that could replace many physical objects with digital alternatives, making tools and experiences more accessible and affordable. The discussion explores how AR glasses might eventually become as common as smartphones, fundamentally changing how we interact with digital information and potentially reducing our dependence on physical manufacturing.
Watch at: https://www.youtube.com/watch?v=BrBGHs-EThY&t=s

Zuckerberg highlights the potential impact.

> Think about how many of the things that we have in our lives actually don't need to be physical. They can be digital and think about how much better and more affordable and accessible they're going to be when they are.
>
> - *Quote from Mark Zuckerberg*

This vision suggests a future where many physical objects could be replaced by virtual counterparts, potentially leading to:

1. Reduced manufacturing and environmental impact
2. Increased accessibility to various tools and experiences
3. More affordable alternatives to expensive physical products

2.3.7 Conclusion

Augmented Reality technology is rapidly evolving, offering new ways to blend digital information with our physical world. From mobile AR applications to sophisticated headsets and industrial solutions, AR is finding its place in various sectors of our lives and work. As these technologies continue to advance, we can expect to see even more seamless integration of digital and physical realities, potentially transforming how we interact with information and our environment on a daily basis.

2.4 Mixed Reality (MR) and Hybrid Systems

Mixed Reality (MR) represents a significant portion of the reality-virtuality continuum, blending elements of both physical and digital worlds to create new environments where physical and virtual objects coexist and interact in real time. In recent years, MR capabilities have become increasingly central to mainstream XR devices, with major manufacturers integrating MR features into their flagship headsets. This shift represents a growing recognition that the ability to seamlessly blend virtual content with the physical world is crucial for the future of immersive computing.

Where early MR systems were specialized devices focused solely on augmented or mixed reality, modern XR headsets increasingly incorporate robust MR capabilities alongside their VR features. This trend towards integrated MR reflects a broader understanding that users need to be able to smoothly transition between fully virtual experiences and mixed reality interactions without changing devices.

Meta emphasizes this blending of realities in their latest headsets through features like full-color passthrough, which allows users to see their physical environment in high fidelity while interacting with virtual objects. Their vision for MR includes practical applications like virtual workspaces where multiple virtual screens can coexist with physical desks and keyboards, or fitness applications where virtual instructors can guide users through real-world workouts.

Apple's Vision Pro takes this concept further with what they term "spatial computing," where virtual content is deeply integrated with the physical space. Their approach includes features like the ability to scale and position virtual screens anywhere in the physical environment, eye and hand tracking for natural interaction with virtual elements, and the ability to adjust the blend between virtual and physical reality using a digital crown. Applications range from immersive FaceTime calls where participants appear life-size in your physical space to 3D movies that seem to extend your room into virtual environments.

This convergence of virtual and physical realities in mainstream devices signals a significant evolution in how we think about mixed reality - no longer as a separate technology, but as a fundamental feature of modern XR experiences.

2.4.1 Varjo XR-4: Enterprise Mixed Reality

Varjo has been at the cutting edge of mixed reality technology for a number of years, starting out with the XR-1 onto the latest XR-4. The Varjo XR headsets combine high-resolution virtual reality capabilities with advanced camera systems for seamless integration of real and virtual environments. Below is a video from a XR-1 demonstration. It has only improved since then.

YouTube Video

Varjo XR-1 Mixed Reality Demonstration
This demonstration showcases Varjo's high-end XR-1 headset capabilities, featuring seamless blending of real and virtual environments through advanced camera systems and ultra-high resolution displays. Viewers will see practical applications including automotive design scenarios where virtual car interiors can be overlaid onto real vehicles, demonstrating the precision and quality possible with professional-grade mixed reality systems. The video illustrates how enterprise XR applications can achieve remarkable realism and practical utility in specialized industries.
Watch at: https://www.youtube.com/watch?v=uxlqMEAQd8Q&t=s

Key features of the Varjo XR-4 include:

1. High-resolution VR display
2. Low-latency, high-quality cameras
3. Seamless blending of real and virtual environments

One notable application of the Varjo XR headsets is in automotive design and testing.

The Varjo system demonstrates remarkable mixed reality capabilities—the cameras are fast and high-quality enough that users can safely drive while wearing the VR headset, seeing reality entirely through the display. The system can then overlay virtual elements, such as completely changing a car's interior design in real-time. This level of seamless reality substitution is quite impressive.

2.4.2 Substitutional Reality

Substitutional reality is an innovative approach that blends live camera feeds with pre-recorded 360-degree video content, allowing for seamless transitions between real-time and pre-recorded experiences.

YouTube Video

Substitutional Reality - Blending Live and Recorded 360° Video
This fascinating demonstration shows substitutional reality technology that seamlessly blends live camera feeds with pre-recorded 360-degree video content. Viewers will see how users can be imperceptibly switched between real-time and recorded experiences, enabling complex scenarios where people appear to leave and re-enter rooms from impossible directions. The technology showcases innovative approaches to manipulating temporal and spatial reality in mixed reality environments, opening possibilities for storytelling and experience design that blur the boundaries between live and recorded content.
Watch at: https://www.youtube.com/watch?v=R3EPOZkXgy4&t=s

The system works as follows: 1. Users wear a VR headset equipped with a pass-through camera, initially showing them the real world. 2. The system can switch to a pre-recorded 360-degree video without the user noticing. 3. This enables complex scenarios, such as a person seemingly leaving the room and re-entering from a different direction.

2.4.3 The Void: Physical Props in Virtual Worlds

The Void represents a culmination of mixed reality concepts, creating large-scale experiences that combine physical environments with virtual reality.

YouTube Video

The Void - Large-Scale Mixed Reality Entertainment
This video provides an overview of The Void's groundbreaking approach to mixed reality entertainment, which combines virtual reality headsets with elaborate physical environments. Viewers will see how The Void creates immersive experiences by building real physical spaces that correspond to virtual worlds, incorporating touchable props, surfaces, and environmental effects that align with virtual objects. The demonstration showcases techniques borrowed from magic and illusion to create convincing mixed reality experiences where users can physically interact with virtual environments on a room-scale level.
Watch at: https://www.youtube.com/watch?v=cML814JD09g&t=48s

Key aspects of The Void's approach include: 1. Building physical environments that correspond to virtual landscapes 2. Incorporating touchable props and surfaces that align with virtual objects 3. Leveraging techniques from magic and illusion to direct attention and create convincing experiences

2.4.4 Non-photorealistic AR: Blurring the Lines

An intriguing approach to augmented reality involves processing the video feed of the real world to make it appear more like virtual content.

This approach involves processing the real-world video feed to make reality appear more like virtual content, creating a stylized aesthetic that makes it difficult to distinguish between real and virtual elements. This technique challenges traditional assumptions about how we present mixed reality experiences.

YouTube Video

Non-Photorealistic AR - Stylized Reality Processing
This intriguing demonstration shows an innovative approach to augmented reality where the real-world video feed is processed to appear more like virtual content, creating a stylized visual aesthetic. Viewers will see how reality itself can be transformed to match virtual elements, making it difficult to distinguish between real and virtual objects in the mixed reality experience. This technique challenges traditional assumptions about AR presentation and opens new possibilities for creative expression and artistic applications in mixed reality environments where visual coherence takes precedence over photorealism.
Watch at: https://www.youtube.com/watch?v=gb79GliV370&t=45s

This approach challenges our assumptions about the nature of reality in mixed reality experiences and opens up new possibilities for creative expression and immersive storytelling.

2.4.5 Spatial Understanding

Modern MR systems have evolved to include sophisticated spatial understanding capabilities. These systems can: - Automatically detect and map physical spaces - Identify common objects like furniture and surfaces - Create persistent digital overlays that maintain their position in physical space - Enable shared experiences where multiple users can interact with the same virtual content anchored in physical space

This environmental understanding enables applications like: - Virtual workspace setups where digital screens persist between sessions - Intelligent object placement that respects physical surfaces and obstacles - Shared MR experiences where multiple users can collaborate in the same augmented space - Adaptive interfaces that adjust based on the available physical space

2.4.6 Digital Twins: Replicating Real Environments in VR

One way that spatial understanding can be used is to create complete digital replicas of real-world spaces, known as digital twins. While basic spatial understanding allows MR systems to detect and map spaces in real-time, digital twins take this concept further by creating precise virtual replicas that can be used for planning, simulation, and prototyping. This concept was demonstrated in a project where a VR application was matched to a physical apartment.

This project created a VR application matched to a precise digital twin of a real apartment. Users could walk around the virtual space, sit on the sofa, and interact with various elements using the Oculus Quest's hand tracking to control virtual cockpit interfaces that corresponded to real-world furniture and spatial layouts.

YouTube Video

Digital Twin VR Environment - Physical Space Replication
This demonstration showcases a VR application that precisely replicates a real apartment as a digital twin, allowing users to interact with virtual controls and interfaces while navigating a space that matches their physical environment. Viewers will see how the Oculus Quest's hand tracking capabilities enable interaction with virtual cockpit-style controls that correspond to real-world furniture and space layouts. This approach demonstrates how digital twins can be used for prototyping AR designs within VR environments, creating unique hybrid experiences that blend VR immersion with real-world spatial awareness.
Watch at: https://www.youtube.com/watch?v=sv6T-tg6RL4&t=s

Among other things, this approach allows for prototyping AR designs within a VR environment, offering a unique blend of VR and AR concepts.Digital twins demonstrate how sophisticated spatial understanding can enable not just real-time interaction with virtual content, but long-term planning and modification of spaces through persistent digital replicas.

2.4.7 Conclusion

Mixed Reality and hybrid systems represent the cutting edge of immersive technologies, blending the physical and digital worlds in increasingly sophisticated ways. From high-end systems like the Varjo XR-4 and the Apple Vision Pro to creative approaches like substitutional reality and non-photorealistic AR, these technologies are pushing the boundaries of what's possible in immersive experiences. The mainstreaming of MR features in consumer

devices has accelerated development across the field, from sophisticated spatial understanding to digital twins, while specialized applications continue to explore new possibilities in specific domains.

As MR technologies continue to evolve, we can expect to see even more innovative applications that challenge our perceptions of reality and open up new possibilities for interaction, entertainment, education, and professional applications. The future of mixed reality promises to create increasingly seamless and intuitive ways of blending our physical and digital worlds, driven by both broad consumer adoption and specialized enterprise innovation.

2.5 Emerging XR Technologies

As the field of extended reality (XR) continues to evolve, new technologies are constantly emerging that push the boundaries of what's possible in immersive experiences. This section explores some of the cutting-edge developments in XR, focusing on haptics, advanced tracking systems, and other innovative approaches to enhancing immersion and interaction.

2.5.1 Advanced Haptic Technologies

Haptic feedback represents one of the most promising emerging areas in XR technology, with researchers developing innovative ways to provide tactile sensations in virtual environments. These advancements include haptic gloves, advanced force feedback systems, and novel approaches like ultrasonic haptics that create tactile sensations in mid-air.

For a comprehensive exploration of haptic technologies, implementation techniques, and design best practices, see Section 5.7.

Additionally, emerging techniques like Galvanic Vestibular Stimulation, which address motion sickness through vestibular system manipulation, are covered in Section 5.4.7.

2.5.2 Advanced Tracking and Interaction Systems

2.5.2.1 Project Northstar: Pushing the Boundaries of AR

Project Northstar, developed by Ultraleap (formerly LEAP Motion), represents an exploratory venture into the future of augmented reality. While not a commercially available product, it offers open-source instructions for enthusiasts to build their own prototypes.

YouTube Video

Project Northstar - Advanced Hand Tracking AR
This demonstration showcases Project Northstar, an open-source AR headset prototype developed by Ultraleap that pushes the boundaries of hand tracking and interaction in augmented reality. Viewers will see advanced hand tracking technology that enables natural interaction with virtual objects, including hand augmentations and novel gesture-based controls. The project explores innovative ways to interact with completely virtual objects using physical hand movements in real space, demonstrating how advanced tracking can create compelling AR experiences where virtual content responds naturally to hand gestures and movements.
Watch at: https://www.youtube.com/watch?v=7m6J8W6Ib4w&t=s

Key features of Project Northstar include:

1. Advanced hand tracking
2. Augmentations to hands for enhanced interaction
3. Exploration of novel ways to interact with virtual objects in physical space

Ultraleap's particular strength lies in hand tracking technology and hand augmentations, exploring innovative interaction methods. This enables users to interact with completely virtual objects using natural body movements within their physical reality, creating compelling hybrid experiences.

For comprehensive coverage of hand tracking and gesture recognition technologies, implementation techniques, and best practices, see Section 5.8.

2.5.2.2 Redirected Walking and the Unlimited Corridor

Redirected walking is a technique that allows users to explore seemingly infinite virtual spaces within a limited physical area. This is achieved by subtly manipulating the user's perception of movement.

YouTube Video

Redirected Walking - The Unlimited Corridor
This impressive demonstration shows redirected walking technology that allows users to explore seemingly infinite virtual spaces within a limited physical area by subtly manipulating their perception of movement. Viewers will see how a cleverly designed physical wall structure can fool users into believing they are walking along an infinitely long, straight corridor when they are actually walking in a curved path. This technique demonstrates advanced spatial manipulation in VR, enabling large-scale virtual exploration in small physical spaces by exploiting human perceptual limitations and spatial orientation.
Watch at: https://www.youtube.com/watch?v=THk92rev1VA&t=s

This represents one of the more impressive recent developments in redirected walking. The cleverly designed wall structure can trick users into believing they're walking along an infinitely long, straight corridor when they're actually following a curved path.

2.5.3 Emerging Display Technologies

2.5.3.1 Light Field Displays

Light field displays represent an emerging display technology that promises unprecedented levels of realism and interactivity in immersive experiences.

YouTube Video

Light Field Display Technology - Spherical 3D Playback
This demonstration showcases cutting-edge light field display technology that enables viewers to see properly rendered 3D views of scenes from multiple perspectives without special glasses. Viewers will observe how light field displays can create natural depth perception and motion parallax, allowing users to look around virtual scenes by moving their head position. The technology demonstrates how spherical light fields can be viewed from inside a volume, providing convincing 3D visualization that shifts perspective naturally as users move left, right, forward, back, up, or down, representing a significant advancement toward truly immersive glasses-free 3D displays.
Watch at: https://www.youtube.com/watch?v=OUU2yGHgPQY&t=s

When viewing a spherical light field from inside the volume, you can see properly rendered 3D views of the scene in every direction. The perspectives shift naturally as you move

left and right, forward and back, or up and down, creating convincing depth perception without special glasses.

While still in development, I believe light field displays offer the potential for glasses-free 3D viewing with natural depth perception and motion parallax.

For comprehensive coverage of light field capture technology, neural rendering techniques, video capture systems, and detailed technical implementations, see Section 7.4.

2.5.3.2 Immersive Light Field Video

Recent developments have introduced end-to-end systems for capturing and displaying high-quality, immersive light field video content, extending static light field displays to include temporal elements.

YouTube Video

Light Field Video Capture System - Immersive Content Creation
This video demonstrates an end-to-end system for capturing high-quality, immersive light field video content, extending static light field displays to include temporal elements. Viewers will see the complex camera array setup and processing pipeline required to capture light field video, which enables truly immersive video experiences where users can move and look around within captured scenes. The technology represents a significant advancement in immersive content creation, allowing for the development of video content that provides natural depth perception and viewing freedom, adding a new dimension to traditional video experiences through spatial exploration capabilities.
Watch at: https://www.youtube.com/watch?v=SvRgkXQZIQg&t=s

This technology allows for immersive video experiences where users can move and look around within the captured scene, adding a new dimension to video content.

2.5.4 AI-Enhanced Interaction in XR

Recent advances in artificial intelligence are transforming how users interact with XR environments, enabling more natural and intuitive interactions through natural language processing and contextual understanding. However, the computational demands of running sophisticated AI models in real-time XR applications currently limit widespread deployment.

For a comprehensive exploration of AI's role in XR technologies, including AI-enhanced interactions, content generation, character interaction, and development tools, see Chapter 8.

2.5.5 Conclusion

These emerging XR technologies represent the cutting edge of immersive experiences. From advanced haptics and tracking systems to innovative display technologies, these developments are pushing the boundaries of what's possible in virtual and augmented reality. As these technologies continue to evolve and become more accessible, we can expect to see even more compelling and immersive XR experiences in the future.

For those interested in staying up-to-date with the latest developments in XR technologies, conferences like SIGGRAPH and IEEE VR often showcase cutting-edge research and prototypes in this rapidly evolving field.

2.6 Further Reading

Chapter 2 delved into the various technologies that make up the extended reality (XR) spectrum, from virtual reality (VR) to augmented reality (AR) and mixed reality (MR). We examined the hardware and software components of these systems and explored the concept of the reality-virtuality continuum. To further your understanding of XR technologies and their place on this continuum, explore these resources:

2.6.1 Research Papers

- Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. IEICE TRANSACTIONS on Information and Systems, 77(12), 1321-1329.
  - Introduces the reality-virtuality continuum, a fundamental concept in understanding XR technologies.

3 Creating Virtual Worlds

3.1 Introduction to Game Engines

Game engines are powerful software frameworks that serve as the foundation for creating interactive 3D environments. As noted by Matthew Ball, "Think of the game engine as establishing the virtual universe's laws—the ruleset that defines all interaction and all possibility." While originally designed for game development, these engines have evolved to become central tools for creating all kinds of virtual experiences, from architectural visualization to urban planning.

3.1.1 Understanding Game Engines

Game engines provide a comprehensive set of tools and technologies for handling various aspects of virtual environment development:

- Graphics rendering and real-time visualization
- Physics simulation and interaction handling
- Sound processing and spatial audio
- Input management (keyboard, mouse, VR/AR devices)
- Asset management and scene organization
- Programming and logic systems

This technology has increasingly moved beyond gaming into "serious" applications. As Ball (2022) notes, "As the global economy continues to shift toward virtual worlds, these cross-platform and cross-developer technologies will become a central part of global society. Particularly the next wave of virtual world builders—not game developers, but retailers, schools, sports teams, construction companies, and cities—will likely use these solutions."

3.1.2 The Two Primary Platforms: Twinmotion and Unreal Engine

In our context, we focus on two related but distinct platforms: Twinmotion and Unreal Engine. Both are developed by Epic Games, with Twinmotion being built on Unreal Engine technology but optimized for different use cases.

3.1.2.1 Twinmotion

Twinmotion is a powerful, real-time 3D visualization tool designed for architecture, construction, urban planning, and landscaping professionals. Developed by Epic Games, Twinmotion leverages the Unreal Engine to provide high-quality, interactive visualizations with ease of use.

When you open Twinmotion, you'll find an intuitive interface with direct access to: - A comprehensive asset library of furniture, vegetation, and materials - Simple drag-and-drop functionality for placing objects and applying materials - Real-time lighting and weather controls - Basic navigation tools using WASD keys and mouse control - A straightforward object manipulation system with an easy-to-use gizmo for moving, rotating, and scaling

Twinmotion comes with built-in support for VR, enabling immersive walkthroughs of your projects. It is, however, not possible to implement specific VR interaction designs - for that you need Unreal Engine.

3.1.2.2 Unreal Engine

Unreal Engine is a powerful and versatile game engine that has become a cornerstone in the world of interactive 3D content creation. To truly appreciate the potential of Unreal Engine, it's essential to see it in action.

YouTube Video

Unreal Engine Enterprise Sizzle Reel
This 2019 showcase demonstrates the impressive real-time rendering capabilities of Unreal Engine across enterprise applications beyond gaming. The video highlights photorealistic environments, dynamic lighting systems, and advanced character rendering used in architecture, automotive design, film production, and industrial visualization. Viewers will see how Unreal Engine enables creators to build highly detailed virtual worlds with cinematic quality graphics, real-time global illumination, and sophisticated material systems - all fundamental tools for creating compelling immersive experiences.
Watch at: https://www.youtube.com/watch?v=iDqGtPHAecc&t=s

These videos show what's possible with this kind of technology. This is the enterprise sizzle reel from 2019, and all of these applications you see here are actual products that are being made by companies.

The sizzle reel showcases real-time computer graphics rendering, emphasizing Unreal Engine's ability to create highly realistic environments and characters for various applications

beyond just gaming. Since this video was created the capabilites of Unreal Engine have bee greatly developed, and the tightening integration with Twinmotion (as well as UEFN, Unreal Engine for Fortnite) provides easier entry points while giving access to full power in the Unreal Engine editor.

3.1.2.2.1 Why Unreal Engine?

Unreal Engine stands out for several reasons:

1. **Competitive Alternative**: While Unity is the primary alternative, Unreal Engine offers unique advantages in terms of visual quality and built-in features.
2. **Licensing and Pricing**: As of March 2024, Unreal Engine uses a tiered licensing model:
    - Games: Free to use until reaching $1 million in revenue, then 5% royalty
    - Non-games: Requires a commercial license with annual fees
    - Education: Free for educational institutions and students for learning purposes
3. **Focus on High-End Applications**.

Unreal Engine is more focused on high-end usage, I would say. Unity has a bigger community, but if you're looking at how many *experts* you have using Unity or Unreal Engine, it's a lot more even.

4. **Comprehensive Offerings**:
    - Extensive marketplace of assets and tools
    - Access to source code
    - Quixel Megascans integration (high-quality photogrammetry assets)
    - Twin Motion (architecture and city planning software)
5. **Industry Standard**: Widely used in film, television, and enterprise visualization, making it valuable for career development in these fields.

By mastering these fundamental concepts of 3D graphics and game engine technology, developers can create rich, interactive environments for a wide range of applications beyond just video games.

For more detailed information on using Unreal Engine, refer to the Unreal Engine Documentation.

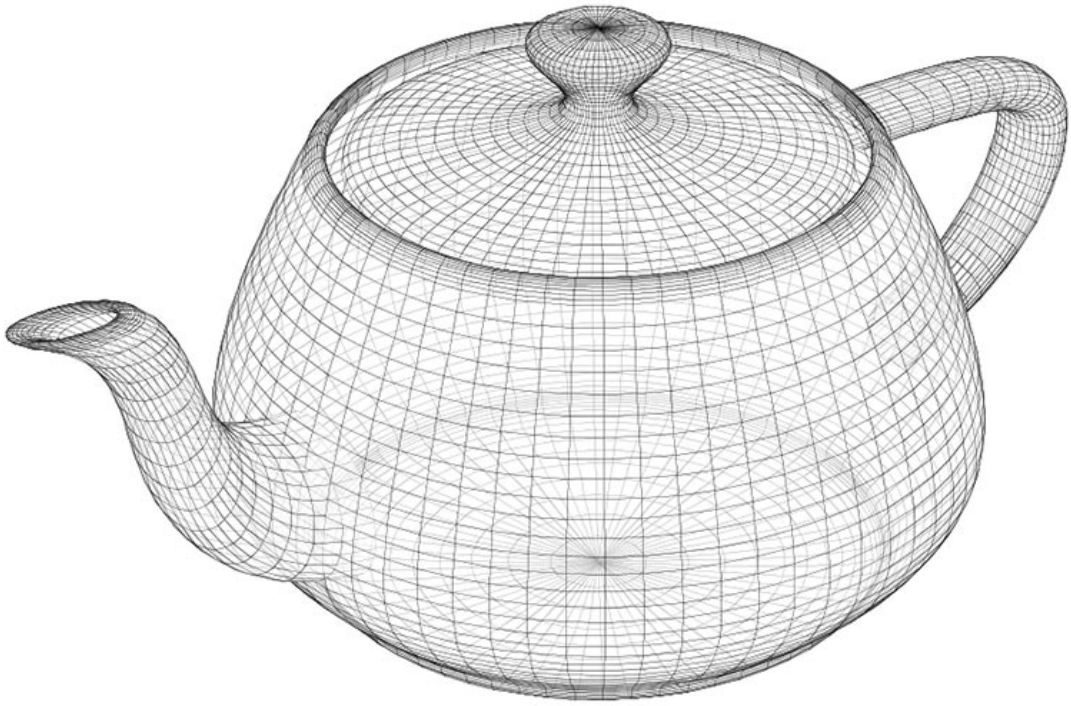
3.1.3 Fundamental Components of 3D Objects

Whether working in Twinmotion or Unreal Engine, all 3D objects consist of two primary elements:

1. **Mesh**: The structural framework that defines the shape of the object.
2. **Surface Materials**: The visual properties applied to the mesh.

3.1.3.1 Mesh

The mesh serves as the structural framework or "wireframe" of a 3D object. Think of it as the skeleton or scaffolding that defines the object's shape. For curved or complex objects, a higher number of polygons is required to achieve a smooth appearance.



A wireframe representation of the classic teapot model used in computer graphics

3.1.3.2 Surface Materials

Surface materials give objects their visual characteristics, analogous to paint or wallpaper in the physical world. At its most basic, a material might simply be a solid color. However, materials can become highly complex, incorporating various properties to achieve realistic or stylized appearances.

Textures can be used to map or drape images onto a surface, much like applying wallpaper to a wall. This process allows for intricate details and patterns to be added to the material, making the 3D object look more realistic and visually appealing. These textures can represent various surface properties such as color, roughness, metallicity, and normal maps to simulate surface details. By applying textures, you can create materials that mimic real-world surfaces like wood, metal, fabric, or stone, enhancing the visual fidelity of your 3D objects.

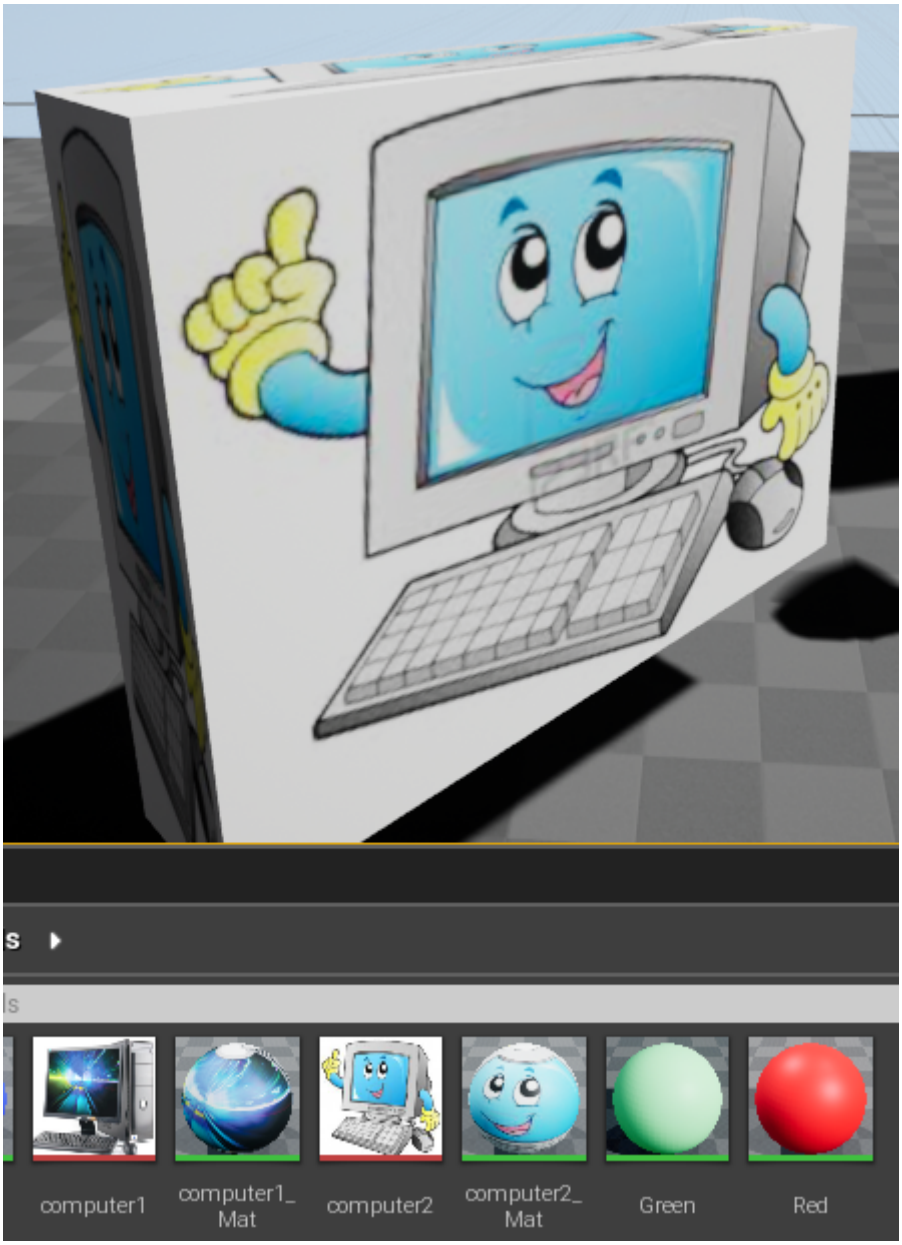


Figure 3.1: Material Example

3.1.3.3 Lighting

Lighting plays a crucial role in creating realistic virtual environments. Both Twinmotion and Unreal Engine offer sophisticated lighting systems. More about that later.

3.1.4 Working with 3D Space

To position and manipulate 3D objects within a virtual environment, we use a coordinate system and transformations. There are several common coordinate systems used in 3D graphics:

Left-Handed Coordinate System: In this system, the thumb, index, and middle fingers of the left hand represent the X, Y, and Z axes, respectively. This system is commonly used in DirectX.

Right-Handed Coordinate System: Here, the thumb, index, and middle fingers of the right hand represent the X, Y, and Z axes, respectively. This system is often used in OpenGL.

Unreal Engine and Twinmotion Coordinate System: Both Unreal Engine and Twinmotion use a right-handed coordinate system where the Z-axis is up. This means: - X-axis: Left to right - Y-axis: Forward and backward - Z-axis: Up and down

Understanding these coordinate systems is crucial for accurately positioning and transforming objects in 3D space. In many 3D applications, including Twinmotion and Unreal Engine, these axes are color-coded for easy identification.

3.1.4.1 Transformations

Transformations allow for the positioning and manipulation of objects in 3D space. They consist of three main operations:

1. **Translation**: Moving the object along the X, Y, or Z axes.
2. **Rotation**: Rotating the object around each axis.
3. **Scaling**: Changing the size of the object along each axis.

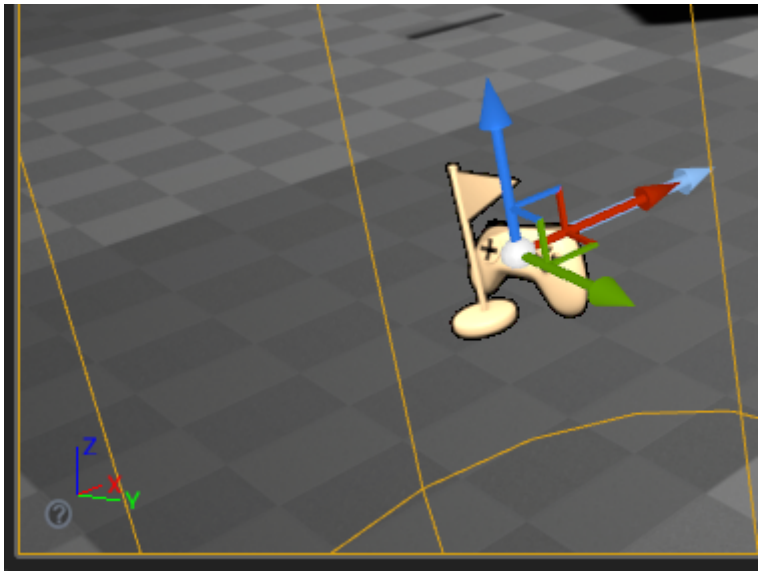


Figure 3.2: Visualization of 3D axes and transformation controls in Unreal Engine

The combination of these transformations determines an object's final position, orientation, and size within the 3D environment.

3.1.5 Getting Started

For those new to these tools, start with Twinmotion for its more approachable interface and workflow, then progress to Unreal Engine as your needs grow more complex. Remember that while these platforms share underlying technology, they serve different purposes and offer different levels of control and customization.

3.2 Building in Twinmotion and Unreal Engine

The modern workflow for creating virtual environments often involves using both Twinmotion and Unreal Engine, leveraging each tool's strengths. While both are based on the same underlying technology, they serve different purposes and offer different workflows.

3.2.1 Getting Started with Twinmotion

Twinmotion excels at rapid visualization and intuitive environment creation, making it an ideal starting point for many projects.

3.2.1.1 Navigation and Basic Controls

Learning to navigate in Twinmotion is straightforward: - WASD keys for "flying" around the environment - Q and E keys for moving up and down - Mouse for looking around - F key to focus on selected objects - Hold mouse over the "gizmo" and drag to move or rotate objects - Drag along specific axes (X, Y, Z) for precise control - Use the yellow center point to anchor objects to the ground

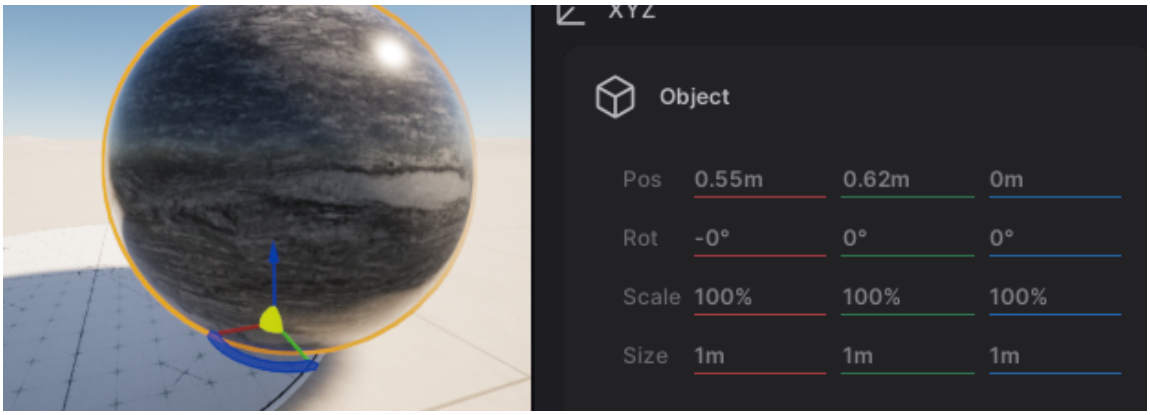


Figure 3.3: Twinmotion Coordinates

3.2.1.2 Setting Up the Environment

To build up the larger structure of the environment, like terrain and buildings, there are a few options in Twinmotion.

1. **Import Your Model**: If you have existing 3D models from design software like SketchUp, Revit, or ArchiCAD, you can easily import them into Twinmotion. You might also find models you can use on digital marketplaces such as Fab (operated by Epic Games, creators of Twinmotion and Unreal Engine).
2. **Use Primitive Shapes**: If you don't have detailed models, you can use Twinmotion's primitive shapes (such as boxes, spheres, and cylinders) to block out buildings and other structures. This is useful for prototyping and planning your environment.

3. **Create Terrains**: Twinmotion provides tools for creating and modifying terrains to fit your project needs. You can:
    - Use the terrain tool to sculpt the landscape, adjusting elevation and creating hills, valleys, and other features.
    - Apply different textures and materials to the terrain to simulate grass, dirt, sand, or other surfaces.
    - Add vegetation, such as trees and plants, to enhance the realism of your environment.
    - Utilize the water tool to create bodies of water like lakes, rivers, and ponds, adding another layer of detail to your scene.

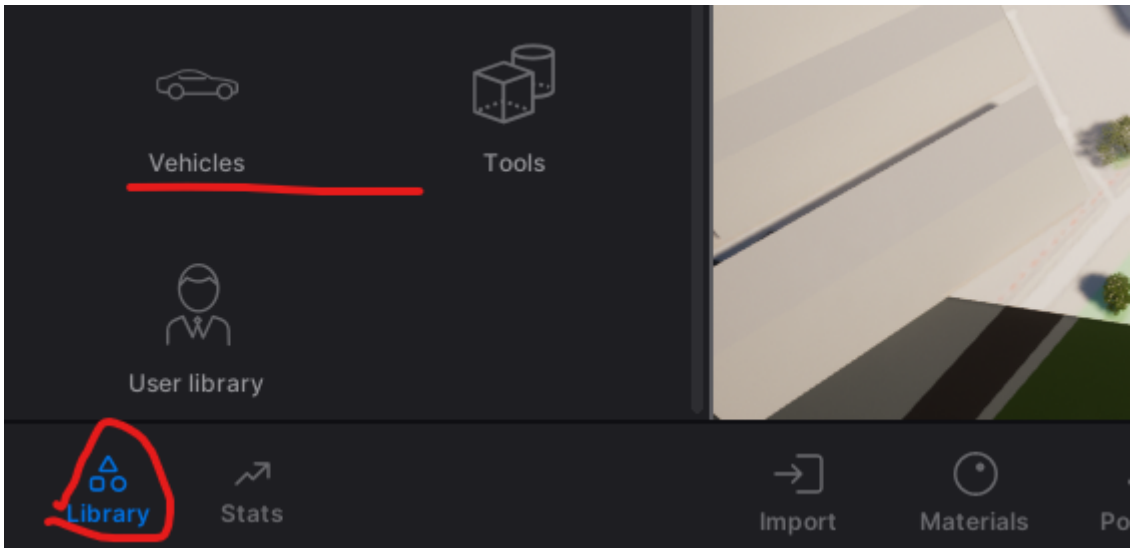


Figure 3.4: Twinmotion Library

3.2.1.3 Furnishing the Environment

1. **Materials and Textures**: Apply materials and textures to your primitive shapes to give them a more realistic appearance. Twinmotion offers a wide range of materials that can be customized to fit your needs.
2. **Objects and Vegetation**: Populate your environment with furniture, vehicles, trees, characters, and other objects from Twinmotion's asset library. This helps create a more immersive and detailed scene.

Twinmotion provides an extensive library of ready-to-use assets:

1. Access the library through the sidebar
2. Browse categories including:
    - Furniture and decorations
    - Vegetation and landscapes
    - Characters and vehicles
    - Materials and textures
3. Drag and drop items directly into your scene
4. Use the Properties panel to adjust object settings

3.2.1.4 Scene Organization

Effective scene management is crucial for larger projects. Build hierarchies to be able to move, rearrange and show/hide groups of objects as a unit.

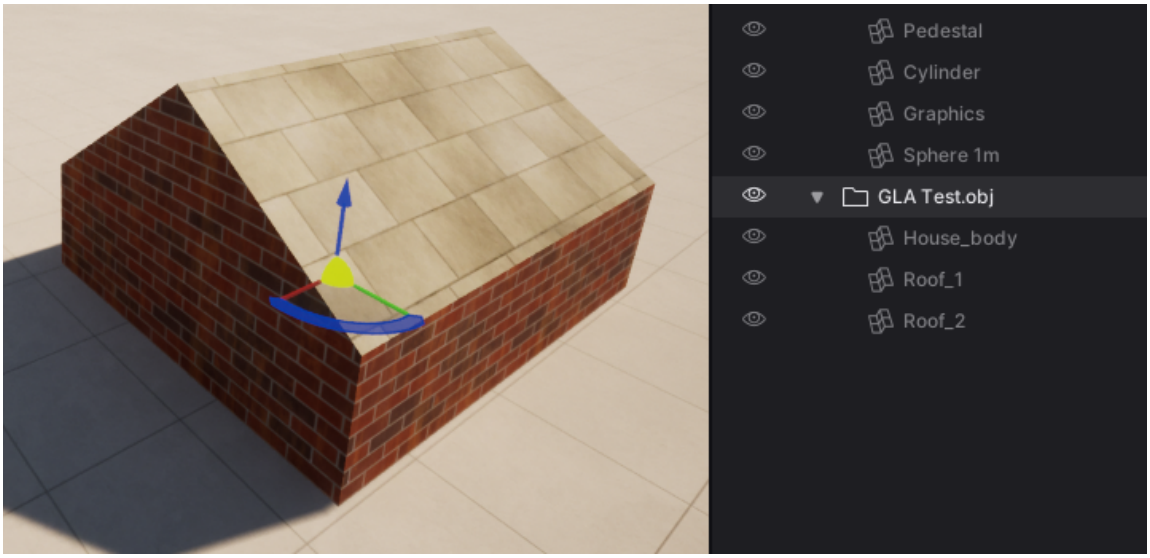


Figure 3.5: Twinmotion Scene List

- Use the scene list to organize objects and groups
- Click the eye icon to show/hide elements
- Create hierarchies to manage complex scenes
- Select groups to move multiple objects together

3.2.1.5 Environment Controls

Twinmotion offers robust environment customization:

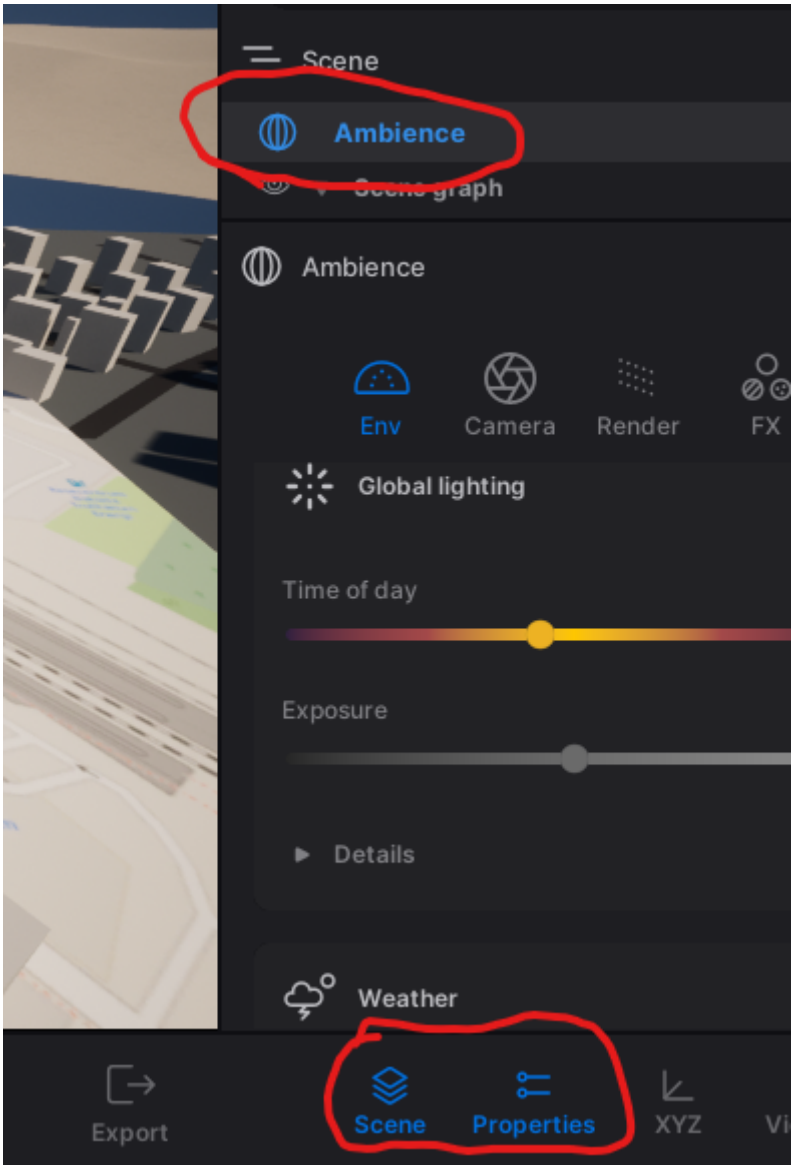


Figure 3.6: Twinmotion Ambience

- Adjust weather conditions and time of day
- Control atmospheric effects

- Modify seasonal vegetation changes
- Set up specific lighting scenarios

3.2.1.6 Working with User Libraries

The User Library system in Twinmotion allows for easy resource sharing: 1. Add objects and materials using "Add to User Library" 2. Access saved resources through the User Library panel 3. Share the library directory with team members - You may also locate and share individual .tmi files within your UserLibrary folder. The recipient can place these in their own UserLibrary folder to access them in Twinmotion. 4. You can point the User Library to another folder, e.g., a shared folder, under Preferences -> Custom Paths.

3.2.1.7 Exporting to Unreal Engine

Once you have set up and furnished your environment in Twinmotion, you can export it to Unreal Engine for further development. This allows you to take advantage of Unreal Engine's advanced features and capabilities.

1. **Export the Environment**: Use Twinmotion's export functionality to save your environment as a file that can be imported into Unreal Engine.
2. **Import into Unreal Engine**: Open Unreal Engine and import the exported file. You can then continue to refine and develop your environment using Unreal Engine's powerful tools.

Note that the Twinmotion to Unreal Engine Export+Import does not work with animated characters or objects, and requires additional work for terrains. With these lomitations, Twinmotion's ease of use and extensive asset library can be leveraged to quickly set up and furnish 3D environments. By exporting to Unreal Engine your flexibility and potentials to push your project further is greatly enhanced.

For more detailed information and tutorials, visit the Twinmotion Documentation for general information. You can also find more information on the Twinmotion to Unreal Engine Workflow. This documentation includes the extra steps you need to do if you want to import Twinmotion landscapes (terrains) into Unreal Engine. In the TwinmotionOverview of the Twinmotion to Unreal Engine Workflow you can read more about the workflow, including details on what is supported.

3.2.2 Building in Unreal Engine

When projects require more complex interactions or custom functionality, Unreal Engine provides the necessary tools and flexibility.

3.2.2.1 Importing Models

One of the primary ways to populate your levels is by importing models. In addition to the path via Twinmotion described above, there are several other methods.

3.2.2.1.1 Migrating from Other Projects

The "Migrate" function in Unreal Engine allows you to copy assets with all their dependencies from one project to another. This is particularly useful when you want to reuse assets across different projects, or when you want to use a few objects from a large Asset pack (see below). Or, perhaps, when you want to integrate work from several students into one project.

To migrate assets:

1. Open the source project containing the desired assets.
2. Locate the asset in the Content Browser.
3. Right-click on the asset and select "Asset Actions" > "Migrate".
4. Choose the Content folder of your target project as the destination.

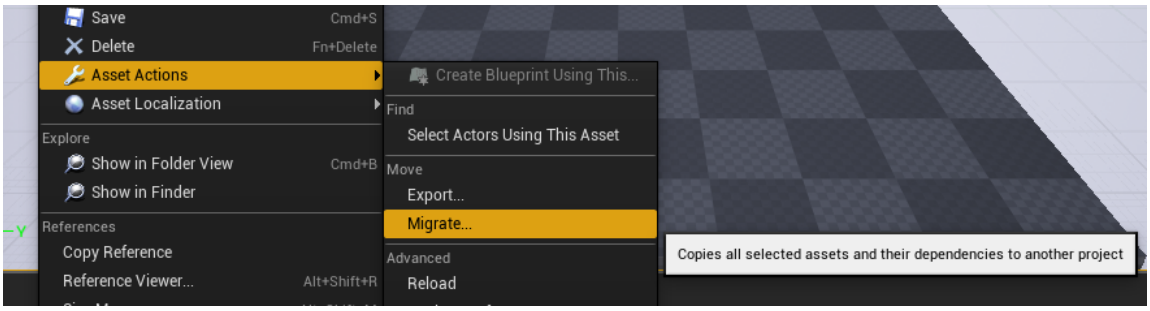


Figure 3.7: Unreal Engine Migrate Function

3.2.2.1.2 Using Asset Packs

For larger collections of assets, such as those available on Fab:

1. Create an empty project or use a minimal template.
2. Add the asset pack to this project.
3. Select specific assets you need.
4. Migrate these selected assets to your main project.

This approach helps keep your main project lean and manageable.

I recommend not adding asset packs directly to your exercises project because then you add everything in that pack to your project. Instead, create an empty project or use a copy of a minimal project and add the asset pack to that one. Then go into that project and pick the particular models or assets that you want to use and migrate them from there over to your exercise project.

3.2.2.1.3 Using Simple Included Shapes

As with Twinmotion, Unreal Engine comes with a set of basic geometric shapes that can be quickly added to your level:

- Boxes
- Spheres
- Cylinders
- And more

These simple shapes are useful for blocking out levels, creating placeholder objects, or even as building blocks for more complex structures.

3.2.2.2 Building Levels

Once you have assets in your project, you can start building your level using various tools and interfaces within Twinmotion or Unreal Engine.

3.2.2.2.1 The Transform Gizmo

The transform gizmo is a crucial tool for manipulating objects in your scene. Simlilar gizmos exist in both Twinmotion and Unreal Engine. They allow you to:

- Translate (move) objects
- Rotate objects
- Scale objects

3.2.2.2.2 World Outliner

The World Outliner provides a hierarchical list of all actors (objects) in your level. It allows you to:

- View all objects in the level in a hierarchy
- Quickly search and filter objects
- Select and/or rename objects
- Organize your level structure

One useful function is to go directly to an object by either double-click it in the Outliner or selecting it and pressing "F" (as in Twinmotion).

3.2.2.2.3 Actor Details Panel

The Actor Details panel displays properties and settings for the currently selected actor. Here you can adjust:

- Transform values (position, rotation, scale)
- Material properties
- Lighting settings
- And many other object-specific properties

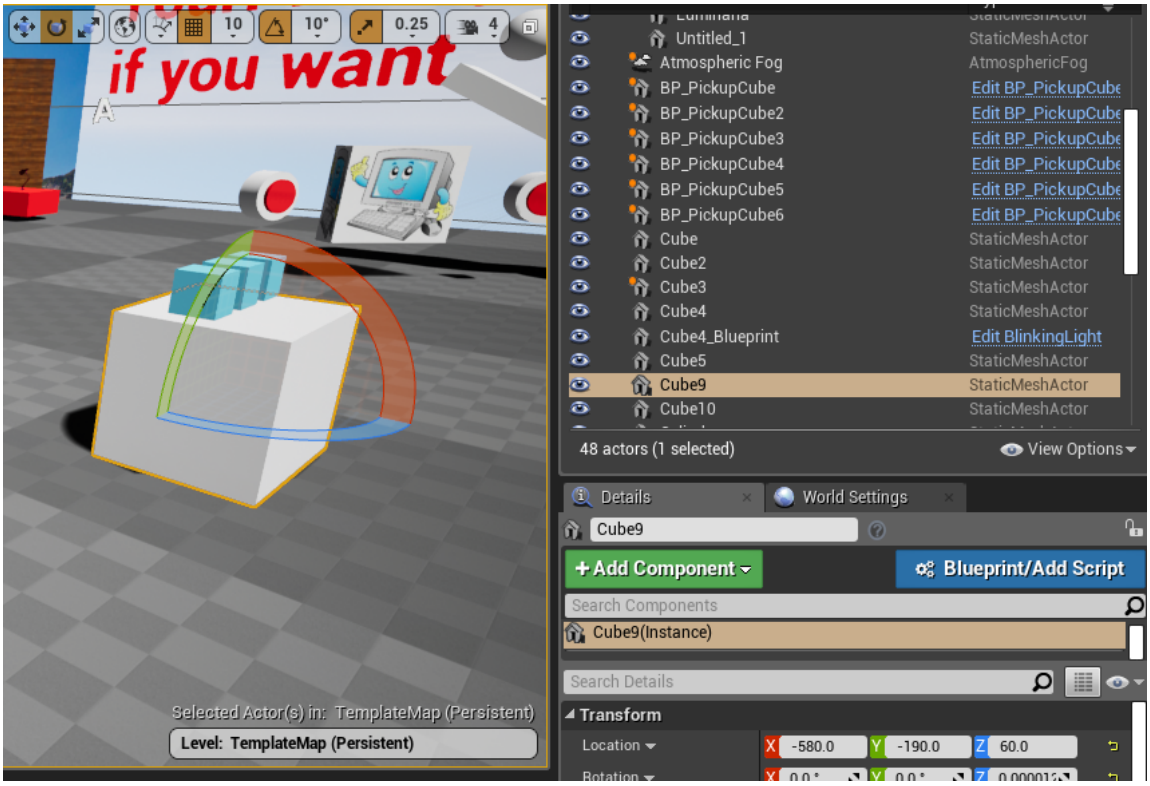


Figure 3.8: Unreal Engine Interface

3.2.2.3 Composite Objects in Unreal

In Unreal Engine, Blueprints are a powerful tool for creating composite objects by combining multiple components into a single actor. This approach allows for flexible and reusable design, making it easier to manage complex objects within your virtual environment. While materials can be set for component meshes within these Blueprints, the primary focus here is on the construction and configuration of these composite objects.

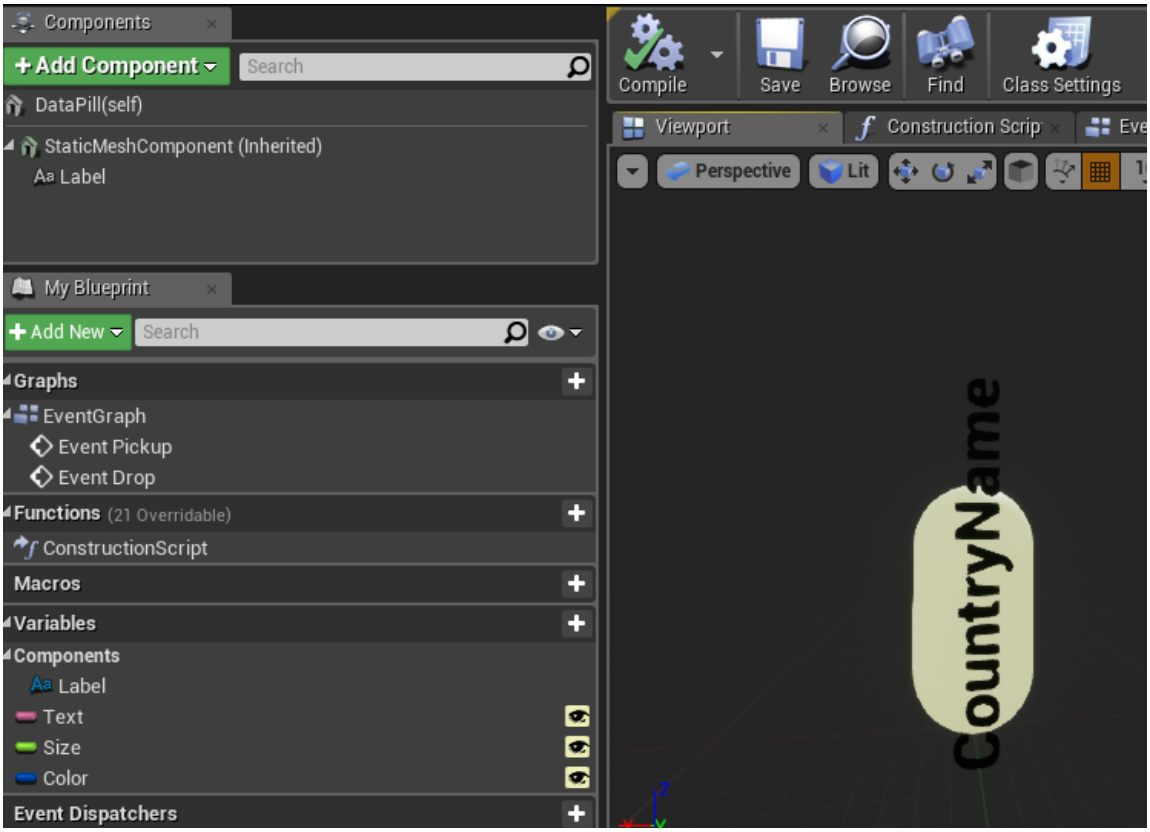


Figure 3.9: Example of a composite actor created with multiple components.

In this example, we see a Blueprint that constructs a labeled object. It combines a mesh (the "pill" shape) with a text component, allowing for easy customization through variables. This is a simple initial use of Blueprints in Unreal Engine, with more advanced applications to be covered in the next chapter.

3.2.2.4 Reality-Capture

It is also possible to populate your virtual 3D environment by creating digital copies of real objects. Reality capture involves digitizing real-world objects or environments to create 3D models for virtual use. This enhances the authenticity of virtual environments by incorporating realistic assets. Common methods include photogrammetry, 3D scanning, and depth sensors. These techniques will be discussed in more detail in a later chapter.

3.2.2.5 Unreal Engine Best Practices

1. **Keep projects lean**: Only migrate the assets you need to keep your project manageable and performance-friendly.
2. **Organize before migrating**: Rename folders and assets before migration if you want a specific structure in your target project.
3. **Use placeholders**: Start with simple shapes to block out your level before adding detailed assets.

By mastering these techniques and tools, you'll be well-equipped to create rich, detailed environments in Unreal Engine, whether you're working on a small prototype or a full-scale project.

For more information on 3D modeling and asset creation in Unreal Engine, check out the official Unreal Engine documentation on Content Creation.

3.2.3 Best Practices for Tool Selection

Choose the appropriate tool based on your project needs:

1. **Use Twinmotion When:**
    - Rapid visualization is priority
    - Working with architectural or urban planning projects
    - Creating quick iterations of design concepts
    - Collaborating with non-technical stakeholders
    - Basic VR walkthroughs are needed
2. **Switch to Unreal Engine When:**
    - Custom interactions are required
    - Complex behaviors need to be implemented
    - Advanced VR experiences are being developed
    - Specific performance optimizations are needed
    - Custom shaders or effects are required

3.2.4 Tips for Efficient Workflow

1. **Start in Twinmotion**
    - Block out basic environments
    - Test different design options

- Get stakeholder feedback early

2. **Prepare for Unreal Engine**
    - Keep scene organization clean
    - Document material and object settings
    - Plan for feature requirements
3. **Optimize Your Process**
    - Use shared User Libraries for common assets
    - Maintain consistent naming conventions
    - Create templates for repeated elements
    - Use characters as scale reference
4. **Consider Performance**
    - Start with simple shapes for blocking
    - Add detail progressively
    - Test performance regularly
    - Use the measurement tool (F1 for help)

By understanding when and how to use each tool, you can create efficient workflows that leverage the strengths of both Twinmotion and Unreal Engine. This combined approach allows for rapid iteration and visualization while maintaining the ability to develop more complex features when needed.

3.3 Working with Materials and Lighting

Creating realistic and visually appealing virtual environments relies heavily on understanding and effectively implementing materials and lighting. Both Twinmotion and Unreal Engine provide powerful tools for controlling these aspects, though with different levels of complexity and control.

3.3.1 Basic Material Concepts

Materials consist of several key components:

1. **Base Color**
    - RGB (Red, Green, Blue) color values
    - Can be solid colors or image-based textures
    - Additional alpha channel (RGBA) for transparency

2. **Textures**
    - Images applied to surfaces
    - Control various surface properties
    - UV coordinates determine how textures map onto surfaces
3. **Surface Properties**
    - Roughness (how smooth or rough a surface appears)
    - Metallic (how metal-like the surface behaves)
    - Opacity (transparency level)
    - Emissive (self-illumination)

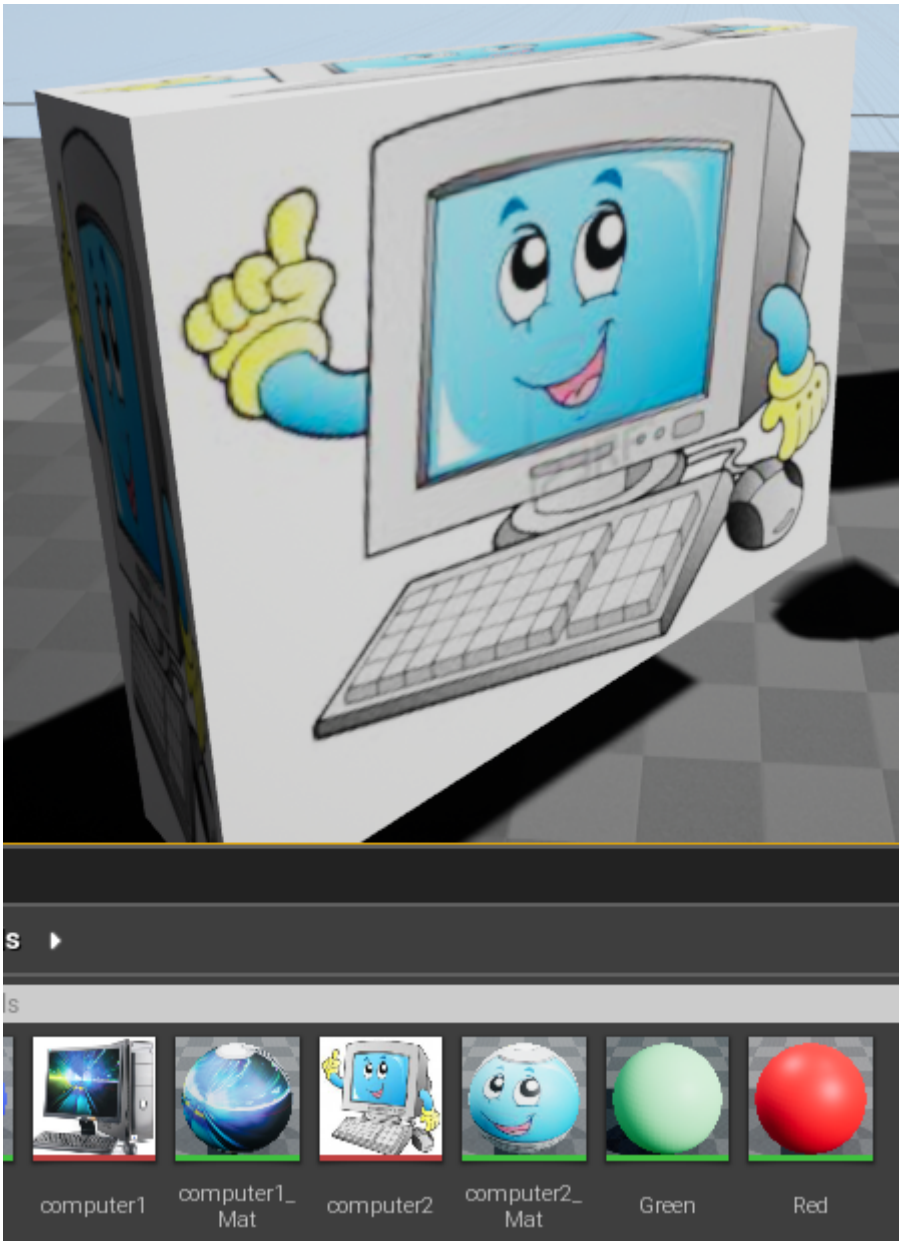


Figure 3.10: Material Example

3.3.2 Working with Materials in Twinmotion

Twinmotion provides an intuitive interface for material management and application.

3.3.2.1 Basic Material Application

1. **Using the Material Library**
    - Browse pre-made materials categorized by type (wood, metal, glass, etc.)
    - Drag and drop materials directly onto objects
    - Switch between "Apply to Surface" and "Apply to Object" modes
2. **Creating Materials from Images**
    - Navigate to Materials -> + (Standard)
    - Access Properties -> Color -> Details -> Texture -> Open
    - Select your image file
    - Adjust scale and tiling through UV properties

3.3.2.2 Adjusting Material Properties

To fine-tune materials in Twinmotion: 1. Select the material 2. Access Properties panel 3. Adjust UV scaling for texture size 4. Use the Material Picker to sample existing materials 5. Modify basic properties like color tint and glossiness

3.3.2.3 Working with Decals

Decals are images that can be "stamped" onto surfaces, adding detail without modifying the base material:

1. Access decals through Library/Objects/Decals
2. Place and position on any surface
3. Create custom decals:
    - Modify existing decals through Properties -> Color -> Details -> Texture
    - Save to User Library with new name
    - Use for signage, weathering, or surface details

3.3.3 Materials in Unreal Engine

Unreal Engine offers more advanced material creation and editing capabilities through its Material Editor.

3.3.3.1 Material Editor Interface

The Material Editor uses a node-based system for creating complex materials:

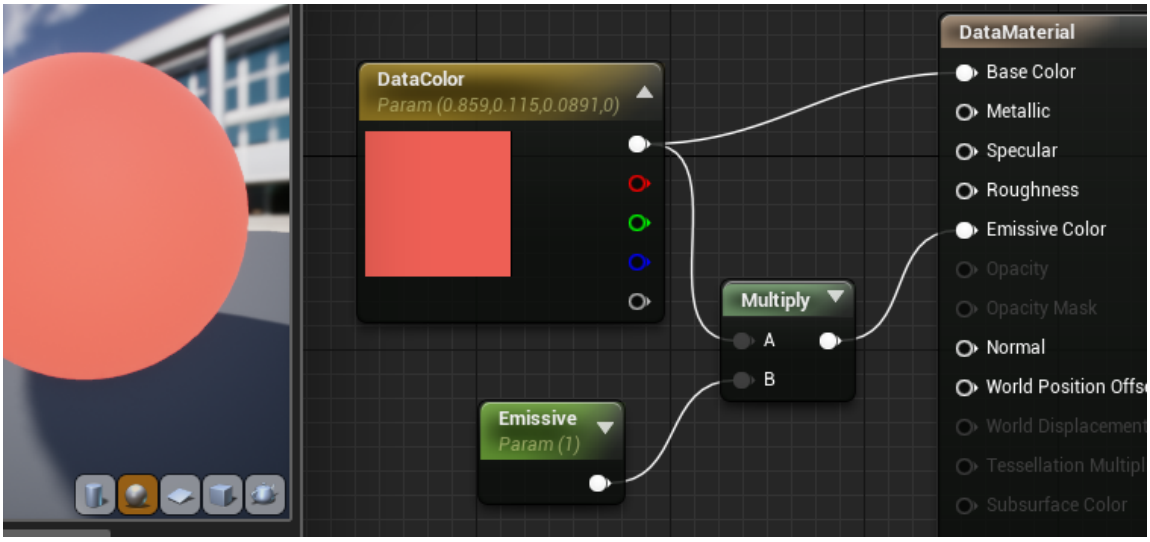


Figure 3.11: Unreal Engine Material Editor

1. **Creating New Materials**

   ```
   Right-click in Content Browser
   Select Create Basic Asset > Material
   Double-click to open Material Editor
   ```

2. **Material Instances**

   - Create variations of base materials
   - Adjust parameters without rebuilding shaders
   - Enable runtime material modifications

3.3.3.2 Creating Materials from Images

Creating materials from images in Unreal Engine is straightforward and efficient. Here's how you can do it:

1. **Import the Image as a Texture**

- Drag and drop your image file (e.g., JPG, PNG) directly into the **Content Browser** within Unreal Engine.
- The image will be imported and appear as a **Texture** asset.

2. **Apply the Texture to an Object**

- Locate the imported texture in the **Content Browser**.
- Simply drag the texture onto the object in your scene viewport.
- Unreal Engine will automatically create a new **Material** using the texture and assign it to the object.

3. **Reuse and Modify the Material**

- The newly created material is saved alongside your assets in the **Content Browser**.
- You can apply this material to other objects by dragging it onto them.
- To further customize the material, double-click it to open the **Material Editor**, where you can adjust properties like color, roughness, metallicness, and more.

This quick process allows you to turn any image into a usable material, enhancing your objects with custom textures efficiently.

3.3.4 Lighting Systems

Lighting is crucial for creating atmosphere and depth in virtual environments. Both platforms offer different approaches to lighting.

3.3.4.1 Basic Lighting Concepts

Light interacts with surfaces in several ways: - Direct illumination from light sources - Indirect bounced light - Surface reflections and scatter - Color interactions between lights and materials

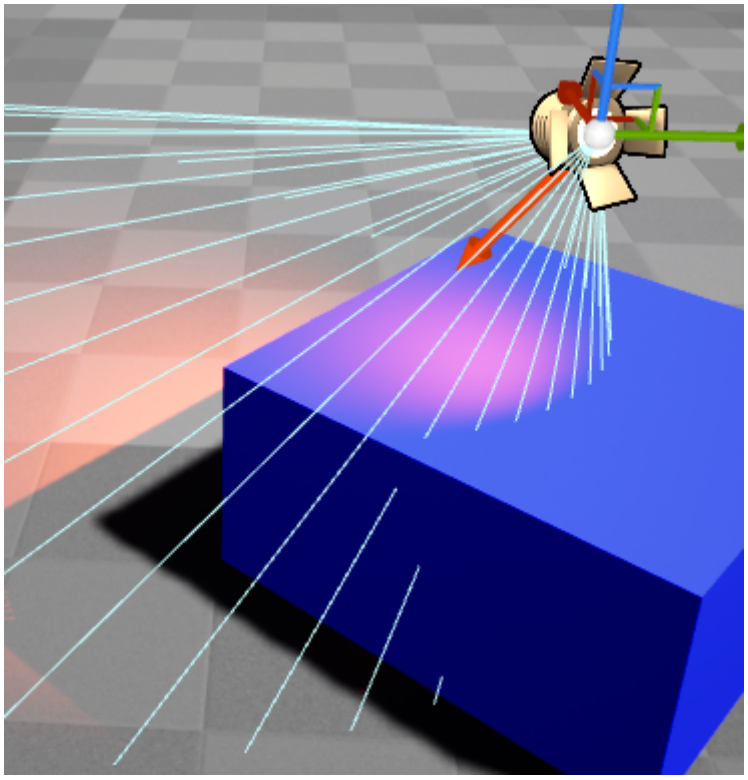


Figure 3.12: Lighting Example

3.3.4.1.1 Simple Lighting Example: Blue Surface + Red Light = Purple

The final color displayed on the screen is a result of the interaction between the surface material properties and the lighting conditions in the scene.

3.3.4.1.2 Advanced Lighting: Light Bouncing and Global Illumination

- **Indirect Lighting**: Light doesn't just illuminate surfaces directly; it also bounces off surfaces, carrying color information with it.
- **Color Bleeding**: A red wall illuminated by light can cast a reddish hue onto adjacent surfaces due to reflected light.
- **Multiple Bounces**: Each bounce can further mix colors, adding to the scene's realism.

3.3.4.1.3 Surface Material Properties

- **Diffuse Reflection**: Determines how much light is scattered uniformly in all directions.
- **Specular Reflection**: Controls the intensity and color of sharp reflections.
- **Ambient Occlusion**: Simulates soft shadows in creases and cavities, affecting the perceived color.
- **Subsurface Scattering**: Allows light to penetrate a surface and scatter internally, influencing the color output.

By accurately simulating these interactions, rendering engines create realistic visuals where materials and lights combine to produce the final colors perceived by the viewer.

3.3.4.2 Lighting in Twinmotion

Twinmotion emphasizes ease of use with its lighting system:

1. **Time of Day**
    - Real-time sun position adjustment
    - Dynamic shadows and lighting changes
    - Atmospheric effects
2. **Artificial Lighting**
    - Simple light placement
    - Basic intensity and color controls
    - Automatic indoor/outdoor adjustment
3. **Tips for Twinmotion Lighting**
    - Artificial lights are subtle during daylight
    - Switch to night view to adjust artificial lighting
    - Use Post Process settings for overall exposure

3.3.4.3 Advanced Lighting in Unreal Engine

Unreal Engine provides more comprehensive lighting control, allowing developers to tailor lighting techniques to their specific needs. The engine supports both baked lighting and real-time global illumination through Lumen.

Baked Lighting vs. Lumen

- **Baked Lighting**: This technique precomputes lighting information and stores it in lightmaps. It offers high-quality visuals with minimal runtime performance impact, making it ideal for VR applications where maintaining high frame rates is critical. However, baked lighting is static and doesn't support dynamic lighting changes during gameplay.
- **Lumen**: Lumen is Unreal Engine's real-time global illumination system. It provides dynamic lighting effects without precomputed lightmaps, allowing for more interactive and responsive environments. While Lumen offers greater flexibility, it comes with increased performance costs and is currently not recommended for VR projects due to these demands.

For VR applications, baked lighting remains the preferred method to ensure optimal performance. More detailed discussions on baking and Lumen will be covered later.

Light Types

Unreal Engine offers a variety of light types to simulate different real-world lighting scenarios. The actual light sources that you can place in your environment are:

- **Directional Light**: Mimics sunlight or moonlight, casting parallel rays in a specified direction. It illuminates all objects equally, ideal for outdoor scenes.
- **Point Light**: Emits light uniformly in all directions from a single point, like a bare light bulb. Useful for simulating localized light sources with spherical influence.
- **Spot Light**: Projects a cone-shaped beam of light, similar to a flashlight or stage spotlight. Allows control over beam angle and falloff for focused lighting effects.
- **Sky Light**: Provides ambient lighting by capturing the sky's illumination, simulating indirect light from the environment. Enhances realism with soft shadows and subtle lighting variations.
- **Rect Light**: Emanates light from a rectangular area, producing soft, diffused illumination. Ideal for simulating light from windows, screens, or luminous panels.

In addition to the standard light sources, Unreal Engine offers functionalities to enhance the realism and flexibility of your lighting:

- **IES Profiles**: Use Illuminating Engineering Society profiles to replicate the precise light patterns of real-world fixtures, adding authenticity with realistic light distribution.
- **Emissive Materials**: Apply materials that emit light to create self-illuminating surfaces, ideal for neon signs, screens, or glowing elements.

- **Light Functions**: Apply dynamic materials to lights to create effects like flickering, pulsating, or patterned illumination, adding interest with animated light behaviors.
- **Volumetric Effects**: Enable lights to interact with particles or fog, creating atmospheric effects like light shafts or beams, and enhancing depth and mood in scenes.
- **Sky Atmosphere and Fog**: Simulate atmospheric scattering for realistic skies, sunsets, and sunrises when used with Directional Lights, adding environmental depth to outdoor scenes.

These features allow you to design rich and immersive lighting environments, tailoring illumination to your project's specific needs.

Light Mobility

The light mobility setting only affects baked lighting. For Lumen, all lights should be treated as movable. Static lights may be automatically ignored when using Lumen, but are key for getting nice lighting when Baking.

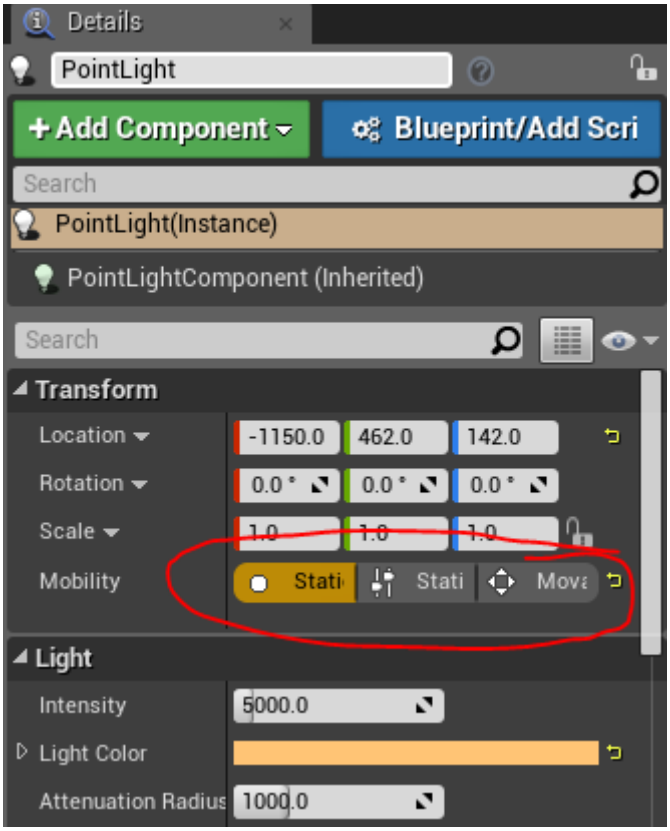


Figure 3.13: Static Light Settings

- **Stationary**: Partially baked, can change color/intensity
- **Static**: Fully baked, highest quality but fixed
- **Moveable**: Fully dynamic, most flexible but costly

Bake Lighting

In 5.4 you need to do the following to bake lighting, or check that it has already been done, depending on which template you are starting out with.

1. **Disable Lumen**:

- Go to **Edit > Project Settings**
- Under the **Rendering** category, set **Dynamic Global Illumination Method** to **None**
- Set **Reflections Method** to **None**

2. **Ensure Lights are Static**:

- Select your lights in the level and set their **Mobility** to **Static**
- You can have a few dynamic lights for interactivity, but most lights should be static.

3. **Build Lighting**:

- Go to **Build > Build Lighting Only** to bake the lighting

To use GPU Lightmass for baking, you need to enable additional settings and ensure your computer meets certain requirements:

1. **Enable GPU Lightmass Plugin**:

- Go to **Edit > Plugins**
- Search for **GPU Lightmass** and enable it
- Restart the engine to apply changes

2. **Turn on Virtual Texture Support**:

- Go to **Edit > Project Settings**
- Under the **Rendering** category, enable **Virtual Texture Support**

Computer Requirements for GPU Lightmass: * A compatible GPU with sufficient VRAM (typically 8GB or more) * Updated graphics drivers * Adequate cooling and power supply to handle the increased load during the baking process

These steps and requirements ensure that GPU Lightmass can function correctly and efficiently, providing high-quality baked lighting for your project.

3.3.4.4 Post-Processing

Both platforms offer post-processing effects to enhance the final image:

1. **Exposure Control**
    - Auto-exposure adaptation
    - Manual exposure adjustment
    - High Dynamic Range (HDR) effects
2. **Color Grading**
    - Overall color temperature
    - Contrast and saturation
    - Color balance adjustments
3. **Additional Effects**

- Bloom and lens flares
- Depth of field
- Ambient occlusion

3.3.5 Best Practices

1. **Material Organization**
   - Use clear naming conventions
   - Create material libraries for reuse
   - Document complex material setups
2. **Lighting Setup**
   - Start with basic lighting
   - Build lighting frequently to check results
   - Consider performance implications
   - Use reference images for comparison
3. **Performance Considerations**
   - Limit dynamic lights
   - Optimize texture sizes
   - Use material instances for variations
   - Balance quality and performance

By understanding and effectively implementing these material and lighting concepts, you can create more convincing and visually appealing virtual environments. Remember to start simple and gradually add complexity as needed for your specific project requirements.

3.4 Optimization for XR Experiences

Creating compelling XR experiences requires careful attention to performance optimization. Unlike traditional desktop applications, XR applications must maintain consistently high frame rates and low latency to provide a comfortable user experience. Modern VR headsets typically require a minimum of 90 frames per second, with some demanding up to 120 fps, while keeping motion-to-photon latency under 20 milliseconds. These requirements exist because any inconsistency in performance can lead to user discomfort or motion sickness.

3.4.1 Performance Considerations Across Platforms

When beginning development, it's important to understand how performance considerations differ between Twinmotion and Unreal Engine. Twinmotion, while excellent for rapid prototyping, handles many optimization decisions automatically but can struggle with complex scenes. Large numbers of unique assets, extensive vegetation, or complex landscapes can impact performance, particularly in VR. When working in Twinmotion, focus on efficient scene organization and be selective with real-time effects like weather systems, which can significantly impact performance.

Moving from Twinmotion to Unreal Engine allows for more precise control over optimization, but requires a deeper understanding of performance factors. The transition process should begin with identifying performance-critical elements in your Twinmotion prototype, then planning how to optimize them in Unreal Engine. This might involve restructuring complex areas, optimizing materials, or implementing more efficient lighting solutions.

3.4.2 Understanding Rendering Optimization

Rendering optimization forms the cornerstone of XR performance. In Unreal Engine, the rendering pipeline must handle creating two views of the scene (one for each eye) at high resolution while maintaining target frame rates. This process can be optimized through several key techniques.

Level of Detail (LOD) systems play a crucial role in managing rendering complexity. Rather than maintaining high detail across all distances, objects can use simpler models when viewed from afar. In VR, LOD transitions need particular attention as users may notice sudden changes in detail more easily than in traditional applications. The key is to balance visual quality with performance, adjusting LOD distances and transition zones to maintain immersion without overwhelming the renderer.

Occlusion culling represents another vital optimization technique. By only rendering objects that are actually visible to the user, significant performance gains can be achieved. Unreal Engine provides tools for setting up occlusion volumes and hierarchical LOD systems, which are particularly effective in complex architectural or urban environments. When implementing occlusion culling, it's important to test in VR specifically, as the wider field of view and head movement can affect what needs to be rendered at any given moment.

3.4.2.1 Note on Nanite

Nanite is Unreal Engine's virtualized geometry system that allows for the real-time rendering of highly detailed assets with massive polygon counts. It eliminates the need for

traditional Level of Detail (LOD) models by automatically adjusting the level of detail based on the camera's view, providing unprecedented visual fidelity.

In general, Nanite isnot performant enough for virtual reality (VR) applications. The demanding computational requirements of Nanite can make it challenging to maintain the high frame rates necessary for comfortable VR experiences, typically 90 frames per second or higher. However, in special cases where a powerful computer is available and lower framerates may be acceptable, it is possible to use Nanite in VR.

3.4.3 Asset and Material Management

Efficient asset management dramatically impacts XR performance. While both Twinmotion and Unreal Engine handle asset loading differently, the principles remain similar. Complex meshes should balance detail with performance requirements, using appropriate polygon counts for their purpose and visibility. Texture resolution and compression settings need careful consideration, especially for standalone VR devices with limited memory.

Materials in XR applications require special attention. Complex material functions that work well on desktop may cause performance issues in VR due to the need to render them twice (once for each eye) at high frame rates. When working with materials, consider using material instances instead of unique materials where possible, and be particularly mindful of expensive operations like dynamic parameters or complex transparency effects.

The material workflow often begins in Twinmotion with simple, effective materials that establish the visual direction. When moving to Unreal Engine, these materials can be refined and optimized, taking advantage of more advanced features while maintaining performance. This might involve combining textures into atlas maps, simplifying complex material functions, or creating more efficient shader variants for VR rendering.

3.4.4 Memory and Resource Management

Memory management becomes particularly crucial in XR applications, especially for standalone VR devices. Unlike desktop applications, VR experiences must maintain high performance while managing resources for two views, often at high resolutions. This requires careful attention to asset loading and unloading, texture streaming, and resource allocation.

Unreal Engine provides powerful tools for monitoring and optimizing resource usage. The built-in profiler allows developers to analyze CPU and GPU usage patterns, identify performance bottlenecks, and monitor memory allocation in real-time. Using these tools effec-

tively requires understanding how to interpret the data they provide and how to address the issues they reveal.

For example, when the profiler reveals that draw calls are impacting performance, you might need to combine static meshes, implement instancing for repeated elements, or adjust the level streaming volume setup. These decisions should be guided by data from the profiling tools rather than assumptions about where performance issues might lie.

3.4.5 Development Best Practices

Optimization should be considered from the beginning of development, not treated as a final polish step. When starting a new XR project, establish performance benchmarks early and test frequently on target devices. This approach helps identify potential issues before they become deeply embedded in the project structure.

Understanding your target platform's capabilities and limitations is crucial. Different VR systems have varying performance characteristics and requirements. For example, standalone VR headsets might require more aggressive optimization of assets and effects compared to PC-tethered systems. Testing on the lowest-spec target device helps ensure a consistent experience across all platforms.

Regular testing in VR throughout development is essential. What works well on a traditional display might present unexpected issues in VR, from performance problems to usability concerns. By maintaining a regular testing schedule in the target VR environment, these issues can be identified and addressed early in development.

Remember that optimization is an ongoing process that requires regular attention and adjustment as your project evolves. By understanding these fundamental concepts and applying them thoughtfully throughout development, you can create XR experiences that maintain both visual quality and performance, providing users with comfortable and immersive experiences.

3.4.6 XR Optimization Checklist

When optimizing your XR experience, verify these key aspects:

Performance Targets - [ ] Maintains 90+ fps consistently - [ ] Motion-to-photon latency under 20ms - [ ] No stuttering or frame drops in VR view

Rendering Efficiency - [ ] LOD system properly configured for VR - [ ] Occlusion culling implemented - [ ] Draw calls optimized and monitored - [ ] Static meshes combined where appropriate

Asset Optimization - [ ] Textures properly sized and compressed - [ ] Material complexity appropriate for VR - [ ] Mesh polygon counts optimized - [ ] Asset loading/streaming configured

Testing Protocol - [ ] Regular testing in target VR device - [ ] Performance profiling data reviewed - [ ] Testing across different VR movement patterns - [ ] Testing in most complex scene areas

Use this checklist during development to ensure you're maintaining optimal performance for your XR experience.

3.5 Further Reading

3.5.1 Official Documentation

- Twinmotion Documentation
- Unreal Engine Documentation
- Epic Games Learning Portal

4 Dynamic Virtual Environments

4.1 Physics Simulations in XR

Physics simulations play a crucial role in creating immersive and realistic virtual reality (VR) experiences. By implementing accurate physics, developers can create environments that feel natural and intuitive to users, enhancing the overall sense of presence in the virtual world.

4.1.1 The Importance of Physics in VR

Physics in VR is not just about creating realistic environments; it's about providing users with a familiar and intuitive way to interact with virtual objects. As demonstrated in early VR applications and games, the ability to pick up, move, and manipulate objects in a physically realistic manner greatly enhances the user experience.

YouTube Video

VR Physics Interaction Demo
Watch as users naturally pick up, manipulate, and throw virtual objects using realistic physics simulation in an early VR application. This video demonstrates how physics-based interactions create intuitive and engaging user experiences in virtual environments, allowing users to interact with objects in a way that feels natural and immersive.
Watch at: https://www.youtube.com/watch?v=Uhh4dA-V2os&t=s

These physics-based interactions allow users to:

1. Explore and experiment freely
2. Apply real-world knowledge to virtual scenarios
3. Engage in rich, multi-faceted interactions

4.1.2 Testing the World Model

One of the most compelling aspects of physics in VR is the ability for users to test their understanding of the virtual world. This concept is beautifully illustrated in the following example:

YouTube Video

Testing VR World Physics
Observe users experimenting with creative physics interactions that weren't explicitly programmed, such as stacking objects in unexpected ways or using physics to solve problems. This video showcases how realistic physics simulation allows users to test their understanding of the virtual world model, enhancing immersion and engagement.
Watch at: https://www.youtube.com/watch?v=zkcRbrnsNp4&t=s

In this scenario, users can attempt actions that aren't explicitly programmed but should theoretically work based on real-world physics. When these interactions succeed, it significantly enhances the sense of realism and immersion.

4.1.3 Fundamental Concepts of Physics in VR

To create these realistic interactions, VR developers must implement several key physics concepts:

4.1.3.1 Force and Velocity

The foundation of physics simulation in VR revolves around forces and velocity:

- **Force** leads to acceleration, which in turn affects velocity
- **Velocity** is defined by both speed and direction

Forces can be applied through:

1. Collisions between objects
2. Scripted events (e.g., programmatically applying force to an object)

4.1.3.2 Types of Forces

Two primary types of forces are commonly used in VR physics:

1. **Impulse**: A momentary push or impact (e.g., hitting an object)
2. **Constant Force**: A continuous application of force (e.g., gravity)

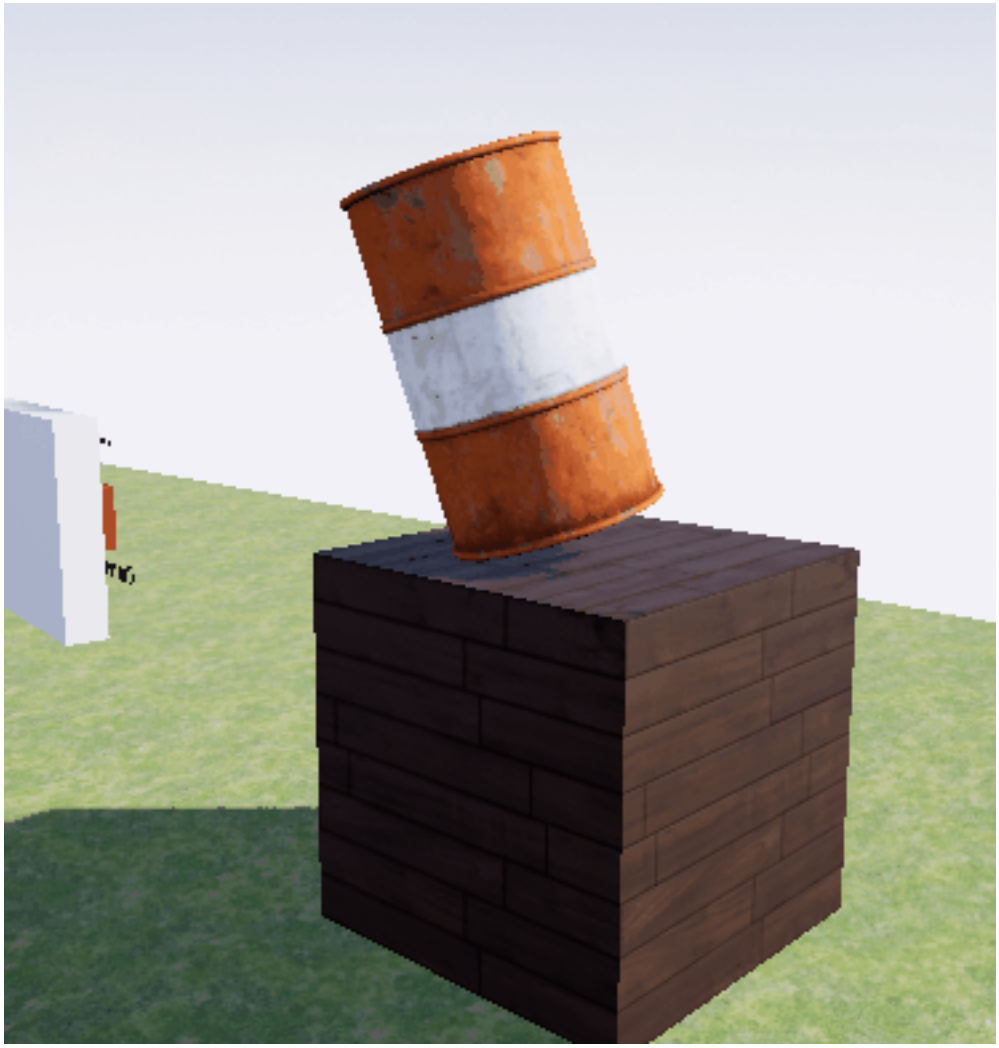


Figure 4.1: Example of adding an impulse to an object with physics simulation.

Illustration of impulse force applied to an object

Here I'm applying an impulse force—hitting it once (well, twice, but one at a time). You can also have constant forces like gravity, which continuously pushes objects downward.

4.1.3.3 Gravity and Collisions

Gravity plays a crucial role in making virtual environments feel natural. It's typically implemented as a constant downward force on all objects. Collisions, on the other hand, allow objects to interact realistically with each other and the environment.

4.1.4 Vectors in 3D Environments

In 3D environments and game engines, vectors play a crucial role in defining direction and magnitude. They are essentially coordinates (X, Y, Z) that specify both the direction and length of an "arrow" in 3D space. This concept is particularly important when dealing with velocity and force in physics simulations.

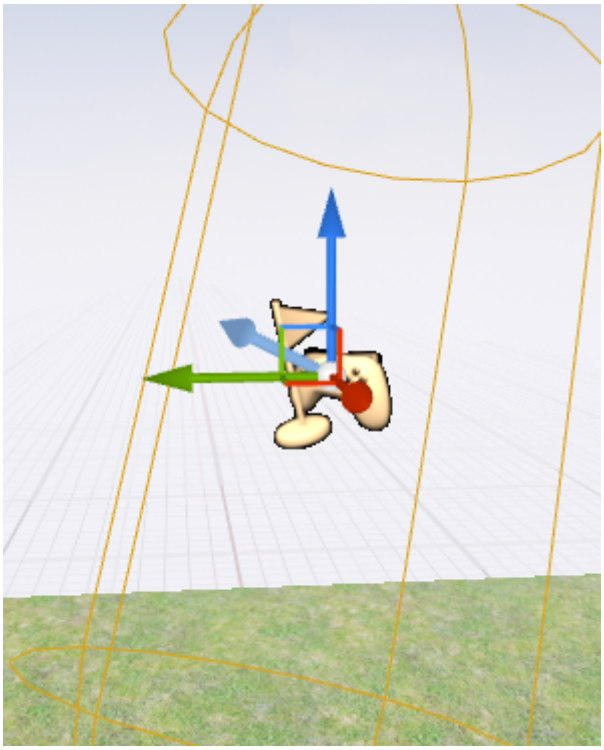


Figure 4.2: Unreal Engine Vector Visualization

As illustrated in the image above, a vector is represented as an arrow pointing in a specific direction relative to the X, Y, and Z axes. This visual representation helps designers and developers understand and manipulate directional forces within the 3D environment.

In practical applications, such as applying an impulse to an object, vectors are used to determine both the direction and magnitude of the force. For example, in Unreal Engine, you might see something like this:

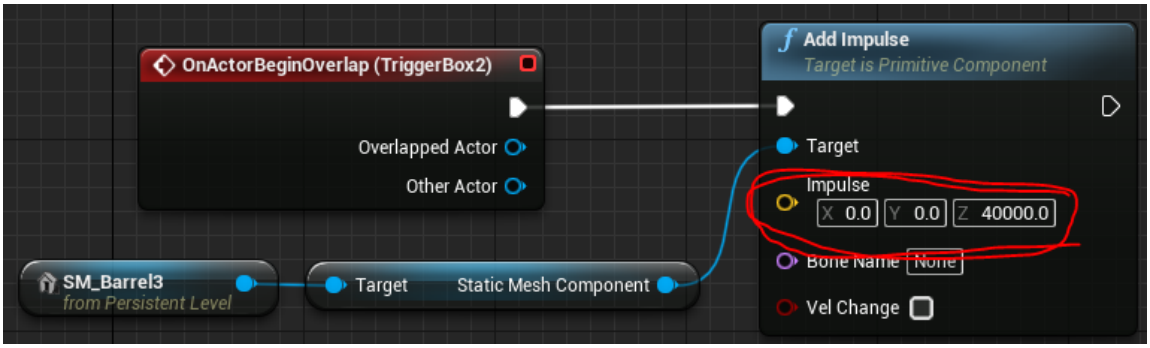


Figure 4.3: Unreal Engine Impulse Vector

Here, we can see a large number associated with the vector.

The reason this is such a large number is because I'm not applying this force over a longer time period. I'm essentially giving the object one big hit.

This demonstrates how vectors are used to apply instantaneous forces in physics simulations, allowing for realistic interactions between objects in the virtual environment.

4.1.5 Implementing Physics in Unreal Engine

Unreal Engine provides a robust physics simulation system that can be easily integrated into VR projects. Here are some key points to consider when implementing physics in Unreal Engine:

1. **Physics Asset Editor**: Use this tool to set up complex physics bodies for skeletal meshes.
2. **Physical Materials**: Define how surfaces react to collisions and friction.
3. **Constraints**: Use physics constraints to create joints and connections between objects.
4. **Force and Torque**: Apply forces and torques to objects using Blueprints or C++.

For more detailed information on implementing physics in Unreal Engine, refer to the Unreal Engine Physics Documentation.

4.1.6 Collision Meshes in Unreal Engine

Before you can create interactive physics-based experiences, you need to understand collision meshes—the invisible geometry that determines how objects interact physically in your virtual world.

4.1.6.1 What Are Collision Meshes?

When you place a 3D object in Unreal Engine, you're actually working with two distinct pieces of geometry:

1. **Visual Mesh**: The detailed, textured model you see rendered on screen
2. **Collision Mesh**: An invisible, simplified shape that the physics engine uses for calculations

These are separate because physics calculations on complex visual meshes would be computationally expensive. Using simpler collision shapes allows the physics engine to run efficiently while still providing believable interactions.

4.1.6.2 Simple vs. Complex Collision

Unreal Engine provides two main approaches to collision geometry:

Simple Collision uses basic geometric primitives:

- Box
- Sphere
- Capsule
- Auto-generated convex hulls

Simple collision is fast and works well for most objects. A crate doesn't need a perfectly accurate collision mesh—a box-shaped collision volume will feel right to users and perform well.

Complex Collision uses the actual mesh geometry:

- More accurate representation of intricate shapes
- Significantly more expensive to calculate

- Useful for detailed architectural elements or mechanical parts where precision matters

For most physics interactions in XR—picking up objects, knocking things over, creating chain reactions—simple collision is the right choice. Reserve complex collision for situations where the extra accuracy justifies the performance cost.

4.1.6.3 Verifying Collision Meshes

A common frustration when setting up physics: you enable simulation, press Play, and nothing happens. The usual culprit? The object lacks a collision mesh entirely.

To check whether an object has collision:

1. In the viewport, go to **Show > Collision**
2. Objects with collision will display their collision geometry as colored wireframes
3. Objects without collision won't show anything

This simple visualization step can save considerable debugging time. Get in the habit of checking collision meshes early when setting up interactive objects.

4.1.6.4 Adding Collision to Imported Assets

Many 3D models imported from sources like Sketchfab or Twinmotion arrive without collision meshes. Here's how to add collision to these objects:

1. **Locate the mesh asset**: Right-click the object in your level outliner and select **Browse to Asset**
2. **Open the mesh editor**: Double-click the asset to open it in the Static Mesh Editor
3. **Generate collision**: In the top menu, go to **Collision > Auto Convex Collision**
4. **Apply settings**: The default settings work well for most objects—click **Apply**
5. **Save**: Don't forget to save the asset (Ctrl+S or File > Save)

You can verify the collision was created by toggling collision visibility in the mesh editor viewport. You should now see a simplified hull wrapping your object.

The auto-generated collision may not be perfect for every object, but it provides a functional starting point. You can refine collision shapes manually if needed, but for physics experiments and prototyping, auto-generated collision is typically sufficient.

4.1.7 Practical Implementation: Setting Up Physics Chain Reactions

One of the most compelling uses of physics in XR is creating chain reactions—where one collision triggers a cascade of events. Think of dominoes falling, explosive sequences, or Rube Goldberg machines. Building on the physics concepts above, let's explore how to implement these patterns. The remarkable thing about implementing these in Unreal Engine is how little setup they require. The physics engine handles all the complexity; you just need to configure the objects correctly.

4.1.7.1 The Setup Checklist

Before chain reactions will work, each object needs specific settings configured. Work through this checklist for every object that should participate in physics simulation:

Essential Settings:

1. **Mobility**: Set to **Movable** (in the Details panel under Transform)
    - Static and Stationary objects cannot be moved by physics
2. **Collision mesh exists**: Verify using **Show > Collision** in the viewport
    - If you don't see collision geometry, add it using the workflow described above
3. **Simulate Physics**: Enable this checkbox (in the Details panel under Physics section)
    - This tells Unreal to apply physics forces and gravity to the object
4. **Collision Preset**: Set to **PhysicsActor** (in the Details panel under Collision section)
    - This preset ensures the object blocks other physics objects and generates hit events
    - You can customize these settings, but PhysicsActor works well for most cases
    - More on collision presets and settings in the next section
5. **Mass**: The auto-calculated mass based on volume usually works well
    - You can override mass manually if needed (in the Physics section)
    - Unrealistic mass ratios (a tiny object that's extremely heavy) can cause unexpected behavior

4.1.7.2 Setting Up a Simple Chain

Let's create a basic domino chain to see these principles in action:

1. **Place objects**: Add several cube static meshes to your level, positioning them in a line with small gaps between them
2. **Apply the checklist**: For each cube, verify all five settings above are configured correctly
3. **Spacing matters**: Leave a small gap between objects—they shouldn't be touching at rest, but should be close enough that when one falls, it contacts the next
4. **Test positioning**: You can temporarily enable Simulate Physics and press Play to test if objects fall correctly—they should all fall straight down without tipping yet
5. **Create the initial impulse**: For the first object in the chain, you need to give it a push to start the reaction:
   - In the first object's blueprint, create a simple Event BeginPlay node
   - Connect it to an Add Impulse node
   - Set the impulse vector (try something like X:500, Y:0, Z:0 to push it sideways)
   - Or manually rotate/position the first object to be tipping toward the next
6. **Press Play**: Watch as the first object falls, strikes the second, which falls and strikes the third, and so on

The physics engine handles everything—force transfer, rotations, realistic timing. Your role is just setting up the initial conditions correctly.

4.1.7.3 Troubleshooting Common Issues

"Nothing happens when I press Play"

- Verify **Simulate Physics** is checked on the objects
- Confirm objects have collision meshes (use Show > Collision)
- Check that you've applied an initial force to the first object

"Objects fall through the floor"

- The floor needs collision too—verify it has a collision mesh
- Check the floor's collision settings—it should block PhysicsBody objects
- If using a Landscape, collision is automatically generated

"The chain stops partway through"

- Objects might be too far apart—reduce spacing
- Mass might be mismatched—very heavy objects won't be moved by light ones
- Initial impulse might be too weak—increase the force value
- Check each object has Simulate Physics enabled (easy to miss one)

"Can't see collision meshes in viewport"

- Verify **Show > Collision** is enabled (check the Show menu carefully)
- Some objects genuinely lack collision—follow the steps above to add it

4.1.7.4 Looking Ahead

This basic setup demonstrates pure physics simulation—objects interacting through physical contact alone. Later in this chapter (Section 4.4), after we explore collision types and overlap events in Section 4.2, we'll look at more complex triggered behaviors. For example, you could have an overlap trigger that spawns a new object mid-chain, or unlocks a constrained object to drop into the sequence. These programmed triggers extend simple physics into rich interactive mechanisms, but they build on the foundation of proper collision and physics setup covered here.

4.1.8 Conclusion

Physics simulations are essential for creating immersive and interactive VR experiences. By implementing accurate physics, developers can create virtual environments that feel natural and intuitive to users, enhancing the overall sense of presence. As VR technology continues to evolve, we can expect even more sophisticated physics simulations that blur the line between virtual and physical realities.

4.2 Collision Detection and Response

Collision detection and response are fundamental aspects of creating interactive and realistic virtual reality (VR) experiences. These systems determine how objects interact with each other in the virtual world, providing the basis for physics simulations and user interactions.

4.2.1 Understanding Collisions in Unreal Engine

In Unreal Engine, collisions are a core component of physics simulations and object interactions. They determine whether objects block each other, overlap, or ignore each other entirely.

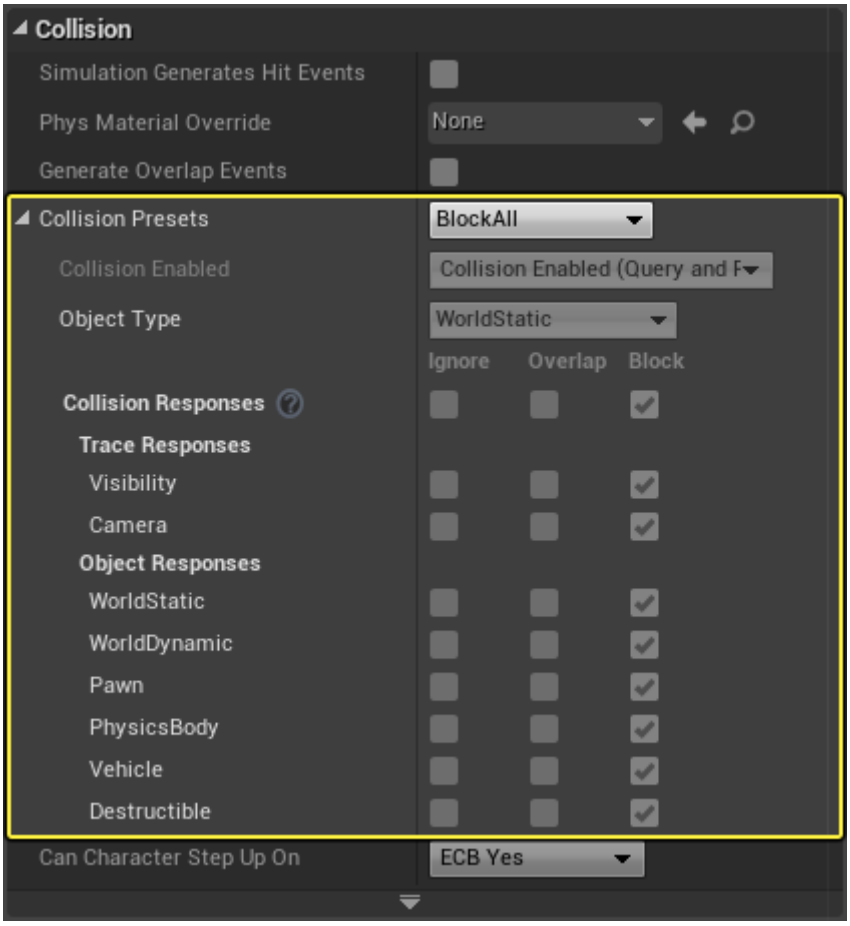


Figure 4.4: Collision Settings

While Unreal Engine provides presets for collision settings, it's crucial to understand what these presets actually do to effectively implement and customize collision behavior.

4.2.1.1 Collision Types: To Block or Not to Block

The core of collision behavior in Unreal Engine revolves around whether objects should block each other, overlap, or ignore each other entirely. This is determined by the collision settings for each object type.

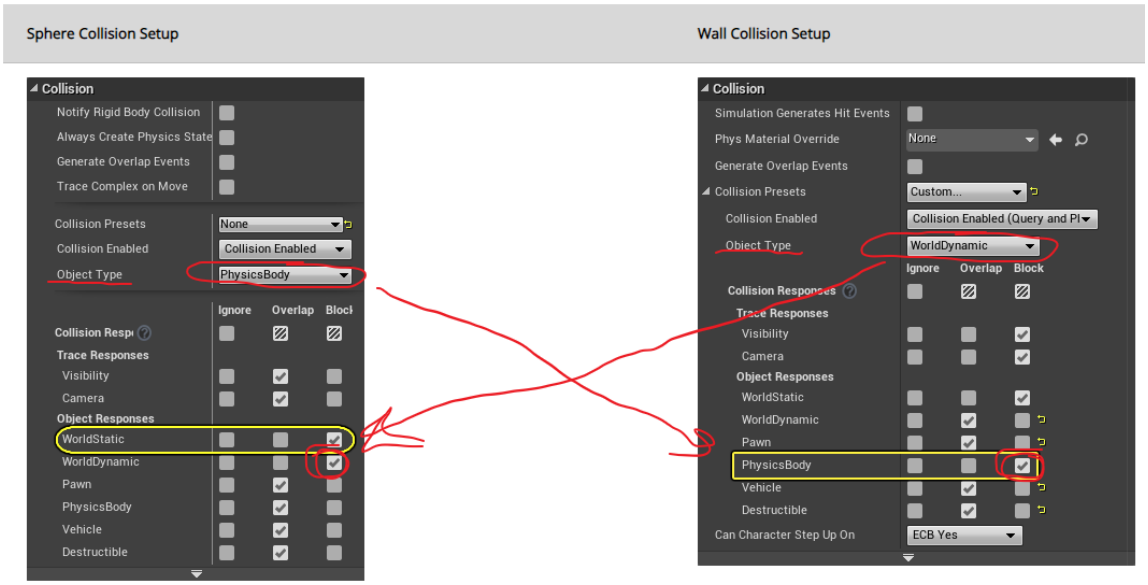


Figure 4.5: Collision Block Types

For a true collision to occur, where objects physically impact and stop each other, both objects need to be set to block each other. For example:

- A wall might be set as "WorldDynamic" (an object in the world that could move but isn't physically simulated)
- A sphere might be set as "PhysicsBody" (an object that moves with gravity and can be pushed around)

If the wall is set to block PhysicsBody objects, and the sphere is set to block WorldDynamic objects, they will collide and block each other when they meet.

4.2.1.2 Object Types

Unreal Engine defines several object types for collision purposes:

- WorldStatic: Objects that never move (e.g., immovable walls)

- WorldDynamic: Objects with scripted movement
- PhysicsBody: Objects with physics-based movement
- Pawn: Objects under user control (typically player characters)

Property	Description
WorldStatic	This should be used for any Actor that doesn't move. Static Mesh Actors are a good example of an Actor that will probably have a WorldStatic type.
WorldDynamic	WorldDynamic is for Actor types that will be moving under the influence of animation or code; kinematic. Lifts and doors are good examples of WorldDynamic Actors.
Pawn	Any player controlled entity should have the Pawn type. The player's character is a good example of an Actor that should receive the Pawn Object Type.
PhysicsBody	Any Actor that will be moving due to the physics simulation.
Vehicle	Vehicles receive this type by default.
Destructible	Destructible Meshes receive this by default.

Figure 4.6: Object Types

Additional object types can be found in the Unreal Engine documentation.

4.2.2 Implementing Collision Detection

4.2.2.1 Hit Events

Hit events are crucial for detecting and responding to collisions in your game logic. To enable hit events:

1. Check the "Simulation Generates Hit Events" option in the object's collision settings.
2. Ensure the objects are set to block each other.

Figure 4.7: Hit Event Settings

When both conditions are met, you can use Blueprint scripting to perform actions when a collision occurs. For example:

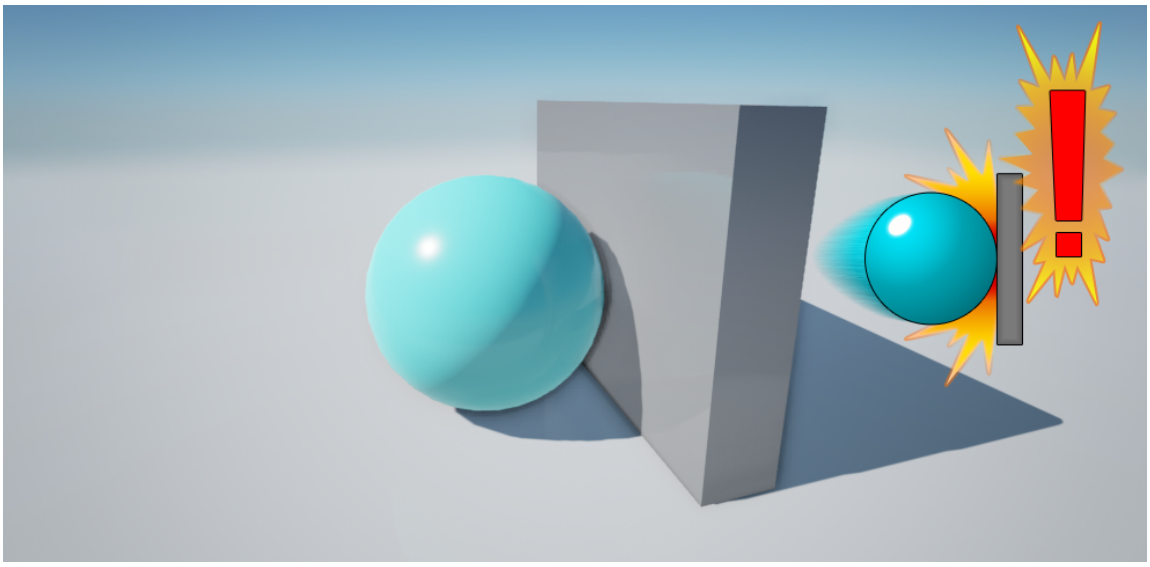


Figure 4.8: Hit Event Example

In this example, when a collision occurs, the text “it was hit” is displayed.

It’s important to note that if objects are set to overlap instead of block, hit events won’t be generated as the objects pass through each other without collision.

4.2.2.2 Overlap Events

Overlap events allow objects to intersect without physically blocking each other. To implement overlap events:

1. Enable “Generate Overlap Events” for all objects involved in the interaction.
2. Set collision responses appropriately (Overlap or Block).

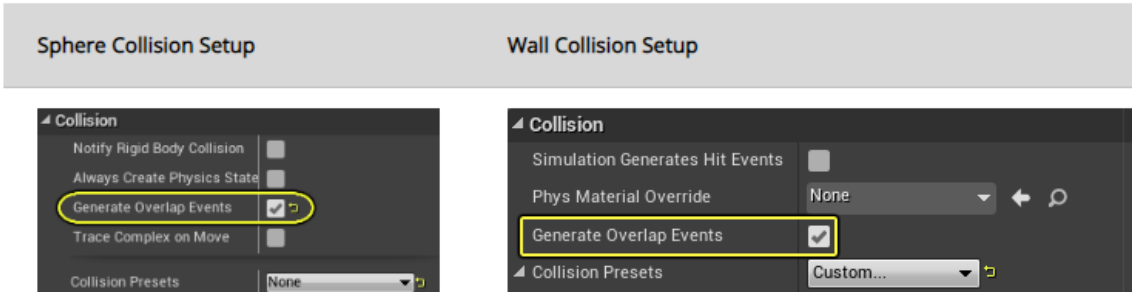


Figure 4.9: Overlap Event Settings

In this case, both the wall and the square need to have ‘generate overlap events’ enabled.

4.2.3 Event Handling Contexts

Unreal Engine provides multiple contexts for handling collision and overlap events:

1. **Level Context**:
   - Connect events to any Actor in the level.
   - Triggered when something hits a specified Actor (whole object).
2. **Actor Context**:
   - Triggered when something hits this Actor (whole object).
   - Applies to all components of the Actor.
3. **Component Context**:
   - Triggered when something hits a specific Component (part of an Actor).
   - Useful for complex Actors with multiple interactive parts.

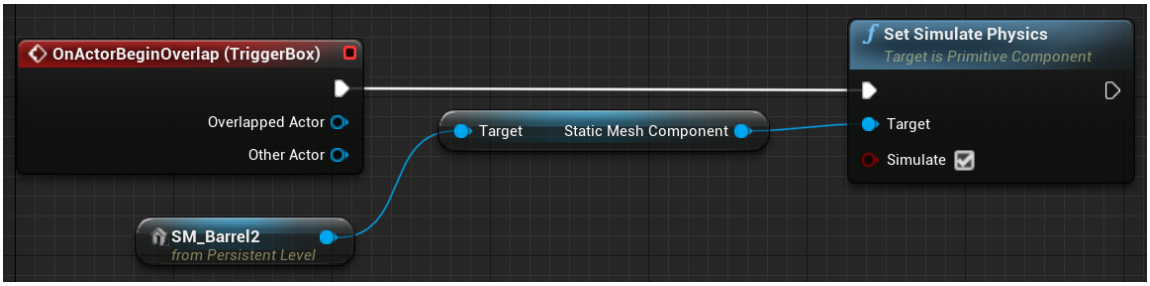


Figure 4.10: Level Overlap Event

To add events to specific components:

1. Right-click the component in the Unreal Editor.
2. Select "Add Event".
3. Choose the appropriate event type (e.g., overlap, hit).

Figure 4.11: Overlap Component Event

4.2.4 Collision Response

Once a collision or overlap is detected, you can implement various responses:

1. **Physical Response**: Objects react based on their physical properties (mass, velocity, etc.).
2. **Gameplay Events**: Trigger specific game events (e.g., damage, pickup items).
3. **Visual/Audio Feedback**: Play particle effects, sounds, or animations on collision.

Implement these responses using Blueprints or C++ in Unreal Engine.

4.2.5 Best Practices for Collision Implementation

1. **Optimize Collision Shapes**: Use simple collision shapes for performance, detailed shapes only when necessary.
2. **Layer Collision Channels**: Organize objects into collision channels to manage interactions efficiently.
3. **Use Trace Functions**: For complex scenarios, use trace functions to detect collisions along specific paths.
4. **Balance Accuracy and Performance**: More accurate collisions can be computationally expensive. Find the right balance for your project.

4.2.6 Conclusion

Effective collision detection and response are crucial for creating interactive and believable VR environments. By understanding and properly implementing these systems in Unreal Engine, developers can create rich, physically accurate interactions in their VR projects.

For more detailed information, refer to the Unreal Engine Collision Documentation.

For a comprehensive video tutorial on collisions in Unreal Engine, watch this:

YouTube Video

Unreal Engine Collision System Tutorial
Comprehensive technical overview by Mathew Wadstein covering collision detection, collision shapes, collision channels, and collision responses in Unreal Engine. This tutorial is essential for understanding and implementing realistic physics interactions in dynamic virtual environments.
Watch at: https://www.youtube.com/watch?v=zZPyMjEWpF8&t=s

4.3 Blueprints and Visual Scripting

Blueprints are a crucial feature in Unreal Engine, providing a visual scripting system for game developers to create interactive functionality without diving into traditional code. This section explores the key aspects of Blueprints, their applications, and how they compare to other programming methods.

4.3.1 What are Blueprints?

Blueprints in Unreal Engine are:

- A visual scripting/programming system
- Used for Actor and Level behavior
- Employed for dynamic construction and configuration

They offer a more accessible alternative to C++ programming within the Unreal Engine environment, making it easier for developers of all skill levels to create complex interactions and behaviors.

4.3.2 Applications of Blueprints

4.3.2.1 1. Actor and Level Scripting

Blueprints can be attached to individual actors or entire levels, allowing for:

- Specific behaviors for objects within the game world
- Global scripts that affect an entire level or world

4.3.2.2 2. Dynamic Construction and Configuration

One of the powerful features of Blueprints is their ability to dynamically construct and configure objects. This is particularly useful for:

- Data-driven design
- Creating flexible, reusable components

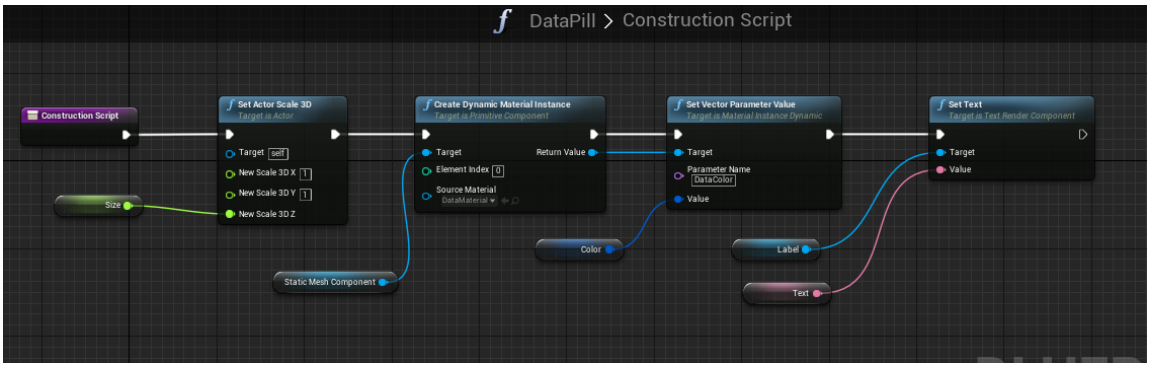


Figure 4.12: Example of a Blueprint construction script.

The image above demonstrates a typical Blueprint workflow. The white lines represent the execution flow, similar to lines of code in traditional programming languages. Each node represents a function or action, with arguments flowing between them.

4.3.2.3 3. Complex and Composite Actors

Blueprints excel at creating more intricate actors:

- Combining multiple components into a single actor
- Similar to "Prefabs" in Unity

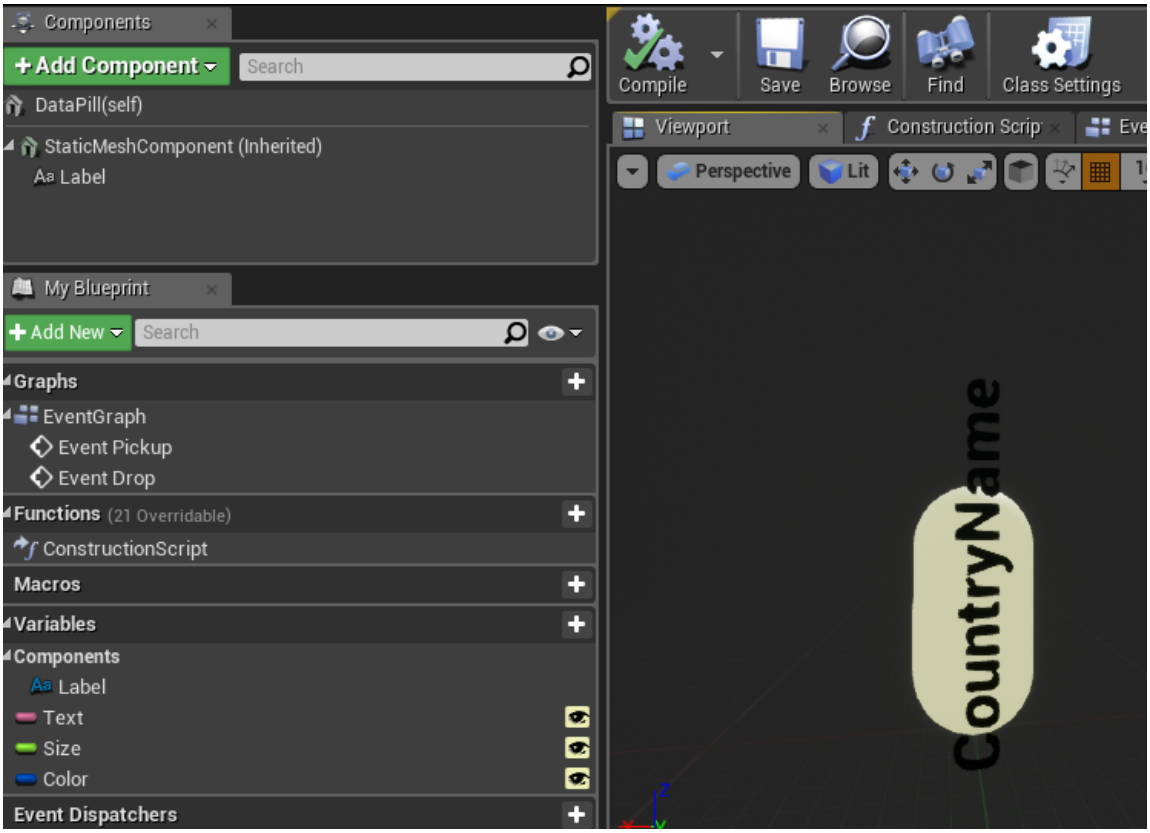


Figure 4.13: Example of a composite actor created with Blueprints.

In this example, we can see a Blueprint that creates a labeled object. It combines a mesh (the "pill" shape) with a text component, allowing for easy customization through variables.

4.3.3 Blueprint Interface

When working with Blueprints, developers interact with several key elements:

1. **Event Graph**: Where most of the scripting occurs, typically triggered by events.
2. **Construction Script**: Defines how the actor is built or modified at runtime.
3. **Components List**: Shows the various parts that make up the actor.
4. **Viewport**: Provides a 3D view of the actor for visual reference.

4.3.4 Blueprints vs. Traditional Programming

To understand how Blueprints compare to more traditional programming methods, it's helpful to see them in context. The following video provides a comparison between Blueprints in Unreal Engine and C# in Unity:

YouTube Video

Blueprints vs Traditional Programming Comparison
Side-by-side demonstration showing how the same interactive functionality is implemented using Unreal Engine's visual Blueprint system versus traditional C++ and C# coding in Unity. This video illustrates the accessibility and power of visual scripting for dynamic environment creation.
Watch at: https://www.youtube.com/watch?v=_TuLsC83yeM&t=s

This video demonstrates how a simple event handling task is implemented using: - Blueprints in Unreal Engine - C++ in Unreal Engine - C# in Unity

It provides valuable insight into how the visual scripting of Blueprints relates to traditional coding paradigms. The video is for Unreal Engine 4 but it works very similarly in Unreal Engine 5.

4.3.5 Types of Blueprints

Unreal Engine primarily uses two types of blueprints:

1. **Actor Blueprints**: These are reusable objects that can be placed in levels. They're ideal for creating interactive elements like doors, switches, or any object that needs specific behavior.
2. **Level Blueprints**: These are specific to a single level and are used for level-wide events and interactions. They're great for quick prototyping and setting up level-specific logic.

4.3.6 Actor Blueprints

- Easily reusable across different levels
- Can be instantiated multiple times
- Ideal for objects with consistent behavior across the game

4.3.7 Level Blueprints

- Quick and easy setup for one specific level
- Cannot be reused in other levels
- Useful for level-specific events and interactions

4.3.8 Working with Events in Blueprints

Events are a crucial part of blueprint programming. They allow you to trigger specific actions in response to in-game occurrences. Here's how you can work with events:

1. **Adding Events**: Right-click on an actor in the level and select "Add Event" or "Jump to Event" if an event already exists.
2. **Level Events**: These are quick to set up and ideal for prototyping. However, consider refactoring into Actor Blueprints later for better reusability.
3. **Event Types**: Common events include "Begin Overlap", "End Overlap", and "Hit Event".

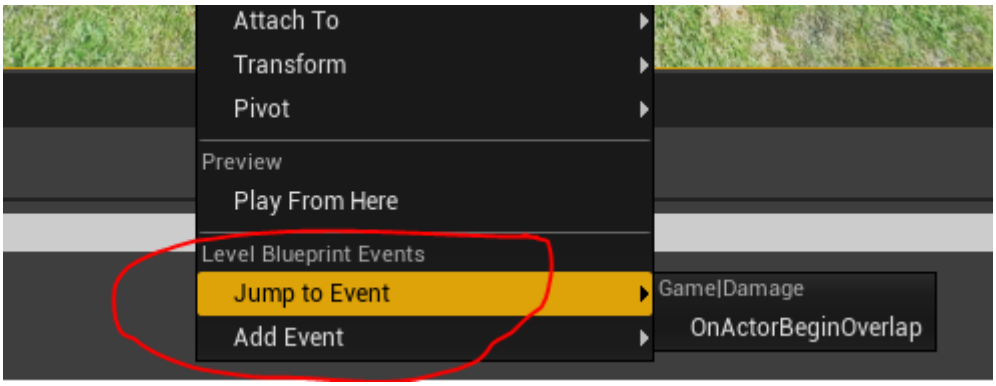


Figure 4.14: Adding Level Events

Once you've added an event, you can implement its functionality in the Blueprint editor. For example, you might add an impulse to an object when it overlaps with a trigger volume:

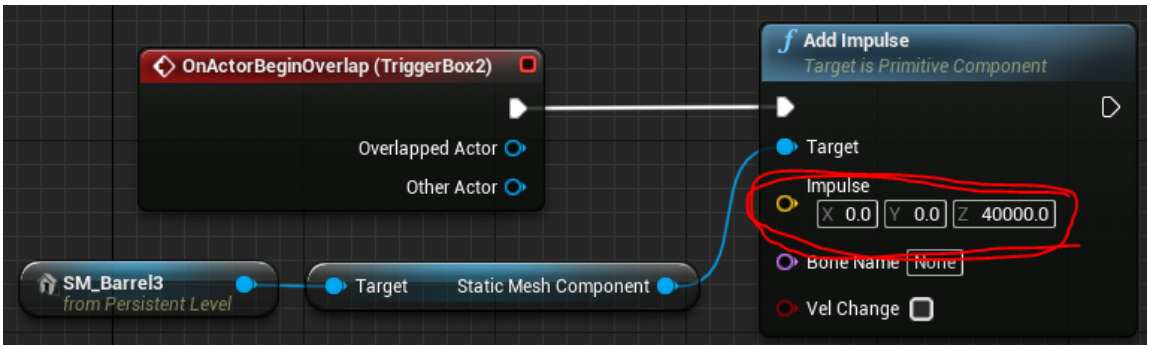


Figure 4.15: Impulse Vector in Blueprint

4.3.9 Blueprint Optimization

While Blueprints are powerful, they can be less efficient than C++ in performance-critical scenarios:

- Convert frequently used Blueprints to C++ for better performance
- Minimize the use of tick events in Blueprints
- Use Blueprint nativization for improved performance

4.3.10 Conclusion

Blueprints in Unreal Engine offer a powerful and flexible way to create game logic and interactivity. They bridge the gap between design and programming, allowing for rapid prototyping and complex behavior creation without the need for extensive coding knowledge. While they can be used for almost any game development task, they are particularly suited for:

- Quick iterations and prototyping
- Designer-friendly logic implementation
- Creating reusable actor templates
- Implementing level-specific behaviors

As you delve deeper into Unreal Engine development, mastering Blueprints will become an essential skill, enabling you to bring your game ideas to life efficiently and effectively.

For more detailed information on Blueprints, refer to the Unreal Engine Blueprint Documentation.

4.4 Event-Driven Programming in XR

Event-driven programming is a crucial paradigm in XR development, particularly in virtual reality (VR) applications. This approach allows developers to create responsive, interactive environments that react to user actions and changes in the virtual world.

4.4.1 Understanding Events in XR

In XR applications, events can be triggered by various sources:

1. User interactions (e.g., button presses, gestures)
2. Collisions between objects
3. Changes in the environment (e.g., time-based events, proximity triggers)
4. System-level occurrences (e.g., application state changes)

Events serve as the bridge between user actions or environmental changes and the application's response, enabling dynamic and interactive experiences.

4.4.2 Implementing Events in Unreal Engine

Unreal Engine provides a robust system for handling events, particularly through its Blueprint visual scripting system.

4.4.2.1 Types of Events

1. **Input Events**: Triggered by user input (e.g., button presses, motion controller movements)
2. **Collision Events**: Occur when objects collide or overlap
3. **Timer Events**: Triggered after a specified time interval
4. **Custom Events**: Developer-defined events for specific gameplay mechanics

4.4.2.2 Event Handling in Blueprints

In Unreal Engine's Blueprint system, events are represented as nodes with execution pins. Here's an example of how events are structured:

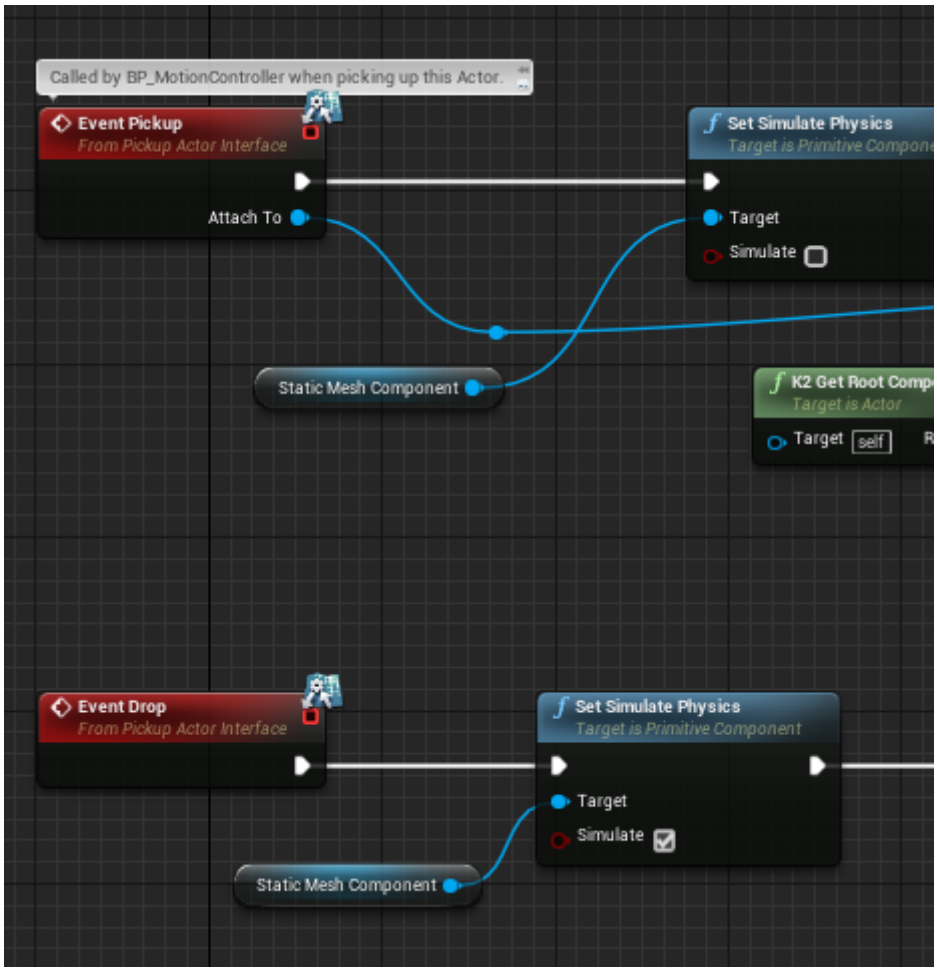


Figure 4.16: Blueprint Events

You can also create custom events with specific functions. We'll explore this further when we look at implementing functionality for actors that can be picked up and dropped, for instance.

4.4.2.3 Adding Events to Actors

To add events to actors in your level:

1. Right-click on an actor in the level
2. Select "Add Event" or "Jump to Event" if an event already exists
3. Choose the type of event you want to add (e.g., Begin Overlap, Hit Event)

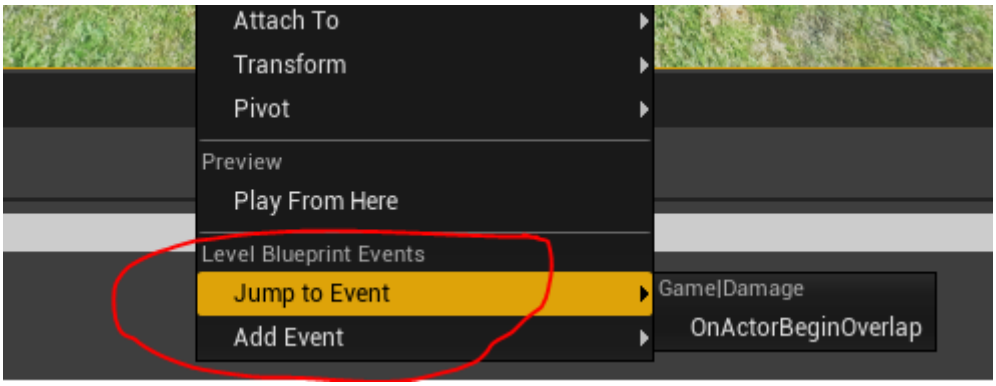


Figure 4.17: Adding Level Events

4.4.3 XR-Specific Event Handling

In XR applications, certain types of events are particularly important:

4.4.3.1 1. Motion Controller Events

These events are triggered by actions performed with VR controllers. For example:

```
Event Motion Controller Thumb Left X
Event Motion Controller Thumb Left Y
Event Motion Controller Trigger
```

These events allow you to respond to user input through VR controllers, enabling interactions like grabbing objects or activating UI elements.

4.4.3.2 2. Head Movement Events

Tracking the user's head movement is crucial in VR. You can use events to respond to changes in the user's viewpoint:

```
Event Tick
-> Break HMDRotation
-> Compare Rotation
```

This setup allows you to detect when the user looks in a certain direction, which can be used to trigger interactions or change the environment.

4.4.3.3 3. Collision and Overlap Events in VR

In VR, collision and overlap events are essential for creating interactive environments. For example:

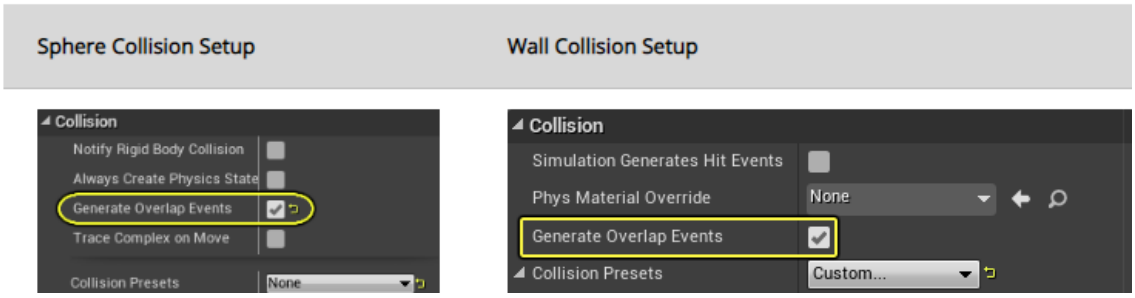


Figure 4.18: Overlap Event Settings

In this case, both the wall and the square need to have 'generate overlap events' enabled.

These events can be used to trigger actions when the user's hand (represented by a motion controller) interacts with virtual objects.

4.4.4 Custom Events and Blueprint Functions

Custom events and Blueprint functions are essential tools for creating complex interactions and reusable logic in Unreal Engine. They allow developers to encapsulate functionality and trigger specific actions within their Blueprints.

4.4.4.1 Custom Events

Custom events are user-defined events that can be called to execute a series of actions. They are useful for organizing and reusing logic within a Blueprint.

Creating a Custom Event: 1. Open your Blueprint and navigate to the Event Graph. 2. Right-click and select "Add Custom Event." 3. Name your event (e.g., "Check Object Placement"). 4. Implement the logic you want to execute when the event is called.

Example:

```
Custom Event "CheckPuzzleSolution"
-> Get All Actors of Class (PuzzlePiece)
-> For Each Loop
   -> Check Piece Position
   -> Branch (If Correct)
      -> Increment Correct Pieces Counter
-> Branch (If All Pieces Correct)
   -> Update Text component "Puzzle Solved"
   -> Trigger Puzzle Solved Event
```

4.4.4.2 Blueprint Functions

Blueprint functions are similar to custom events but are designed to return a value or perform a specific calculation. They help in creating modular and reusable code.

Creating a Blueprint Function: 1. Open your Blueprint and navigate to the Functions section. 2. Click the "+" button to create a new function. 3. Name your function and define its inputs and outputs. 4. Implement the logic within the function.

Example:

```
Function "Calculate Distance"
Inputs: Vector A, Vector B
Outputs: Float Distance
-> Subtract Vectors (A - B)
-> Vector Length
-> Return Distance
```

By using custom events and Blueprint functions, you can create more organized, modular, and reusable Blueprints, enhancing the overall efficiency and maintainability of your projects.

4.4.5 Simple Animation in Unreal

Unreal Engine provides extensive animation systems—skeletal animation for characters, animation blueprints for complex state machines, control rigs for procedural animation, and more. This section focuses on a much simpler subset: animating objects like doors, platforms, and interactive mechanisms. For these cases, two tools are particularly useful: **Timeline** and **Level Sequencer**.

4.4.5.1 Timeline Component

Timeline is the primary tool for script-driven animations within Blueprint actors. It provides a visual keyframe editor that handles smooth interpolation automatically, eliminating the need for manual lerp calculations or tick-based updates.

Key Features:

- **Visual keyframe editor** embedded directly in Blueprint
- **Multiple track types**: Float, Vector, Event, Color, Linear Color
- **Built-in playback controls**: Play, Stop, Reverse, Play From Start, Reverse From End
- **Easing curves**: Linear, ease in/out, or custom curves for natural motion
- **Update output**: Fires every frame during playback, providing interpolated values

When to Use Timeline:

- Simple object movement (doors, platforms, drawers)
- Gameplay-triggered animations (respond to player interaction)
- Quick prototyping of animated behaviors
- Single-object animations where logic lives in the Blueprint

Timeline is fast to set up and keeps animation logic close to the Blueprint that uses it. For a sliding door triggered by player proximity, Timeline provides everything you need.

4.4.5.2 Level Sequencer

Level Sequencer is Unreal's cinematic animation tool, but it can also be used for simple object animations similar to Timeline. Sequencer provides a more powerful editing environment with better support for complex timing and multi-object coordination.

Key Features:

- **Multi-object animation**: Coordinate multiple actors in a single sequence

- **Rich track types**: Transform, materials, visibility, events, and more
- **Visual timeline editor**: Easier to adjust timing and preview animation
- **Reusability**: One sequence can be triggered from multiple Blueprints
- **Blueprint integration**: Use Level Sequence Player component to trigger sequences

When to Use Sequencer:

- Animations that might grow more complex later
- Multi-object coordinated movement
- When you want powerful visual editing tools
- Reusable animations across multiple actors

Sequencer has more overhead for simple cases, but offers flexibility for future expansion. If you think your door animation might later include lighting changes, camera movements, or coordinated sounds, starting with Sequencer saves refactoring later.

4.4.5.3 Choosing Between Timeline and Sequencer

For most simple cases—a door opening, a platform moving—either tool works. **Timeline** is quicker to set up and keeps everything in one Blueprint. **Sequencer** provides more editing power and flexibility. Both can be triggered from the same Blueprint events and controlled with similar logic.

The practical example below uses Timeline, as it represents the most common workflow for simple interactive animations. The same result can be achieved with Sequencer using a Level Sequence asset and Level Sequence Player component instead.

4.4.6 Practical Implementation: Animated Sliding Door

Let's create a sliding door that opens when the player approaches and closes when they leave—a common pattern for interactive environments. This example uses Timeline to handle the smooth animation between open and closed positions.

YouTube Video

Building a Sliding Door with Blueprints and Timeline
Step-by-step tutorial demonstrating Blueprint fundamentals through building a functional sliding door using Timeline animation, trigger volumes, and overlap events in Unreal Engine. This video covers core concepts including components, events, and visual scripting that form the foundation for interactive XR environments.
Watch at: https://www.youtube.com/watch?v=3NpM8v-ukEY&t=s

This example follows the workflow demonstrated in the video above, adapted for XR applications.

4.4.6.1 Setting Up the Blueprint Structure

1. **Create Blueprint Actor**: In the Content Browser, create a new Blueprint Class derived from Actor. Name it "SlidingDoor."
2. **Add Static Mesh components**:
   - Add a Static Mesh component for the door piece that will move (name it "DoorPiece")
   - Add additional Static Mesh components for the door frame (stationary parts)
   - Set the root component to something stationary (like the frame) or a Scene component
3. **Add trigger volume**: Add a Box Collision component (name it "TriggerVolume"). This invisible box will detect when the player enters and exits.
4. **Position and scale**: In the viewport, position the door frame and door piece to form a complete door. Scale the Box Collision to cover the area in front of the door where you want it to trigger.

4.4.6.2 Creating the Timeline Animation

1. **Add Timeline node**: In the Event Graph, right-click and add a Timeline node. Name it "DoorSlide."
2. **Open Timeline editor**: Double-click the Timeline node to open the Timeline editor panel.
3. **Create Float track**: Click the "+ Track" button and select "Add Float Track." Name it "SlideAmount."
4. **Add keyframes**:
   - **At time 0.0 seconds**: Right-click the timeline and "Add Key." Set value to **0.0** (door closed)
   - **At time 1.0 seconds**: Add another key at 1.0s with value **1.0** (door open)
   - These values represent the animation progress: 0 = closed, 1 = fully open
5. **Set animation length**: Adjust the timeline length (default 1.0 seconds works well for a quick slide; use 2.0 for slower movement)

6. **Optional - adjust curve**: Select the keyframes and change the curve type (Auto, Linear, Curve) for different easing feels

4.4.6.3 Connecting the Movement Logic

Now connect the Timeline's output to actually move the door:

1. **Get Timeline Update output**: From the Timeline node, drag out the **Update** execution pin. This fires every frame while the Timeline plays.
2. **Add Set Relative Location node**: Add a "Set Relative Location" node and set the target to your "DoorPiece" component.
3. **Split the Vector**: Right-click the "New Location" pin on Set Relative Location and select "Split Struct Pin." This exposes X, Y, and Z separately.
4. **Add Multiply node**: From the Timeline's "SlideAmount" data output (the float track), drag out and add a "Multiply (float)" node. Set the multiplier value to your desired movement distance (e.g., **200** for 200cm slide upward).
5. **Connect to movement axis**: Connect the Multiply result to the **Z** pin of the split vector (for vertical slide). Use **X** or **Y** for horizontal sliding.
6. **Preserve other axes**: Leave the other vector components (X and Y if sliding on Z) unconnected—they'll maintain the door's starting position on those axes.

The logic flow: Timeline outputs 0-1 → Multiply by 200 → Results in 0-200 range → Applied to Z position → Door slides 200cm up.

4.4.6.4 Adding Trigger Events

Connect the trigger volume to control the Timeline:

1. **Select trigger volume component**: In the Components panel, select "TriggerVolume."
2. **Add overlap event**: Right-click and select "Add Event → Add On Component Begin Overlap."
3. **Add Cast to Character**: From the "Other Actor" pin of the overlap event, add a "Cast to Character" node. This ensures only the player triggers the door, not other objects.

4. **Connect to Timeline**: From the successful cast output (the execution pin below the Character pin), connect to the Timeline's **Play From Start** input.
5. **Add end overlap event**: Right-click TriggerVolume again and add "Add On Component End Overlap."
6. **Add second Cast**: Add another "Cast to Character" from this event's "Other Actor" pin.
7. **Connect to Reverse**: From the successful cast, connect to the Timeline's **Reverse From End** input.

This creates the behavior: player enters trigger → door slides open; player exits trigger → door slides closed.

4.4.6.5 Testing Your Door

1. **Place door instance in level**: Drag your SlidingDoor Blueprint into the level.
2. **Adjust trigger volume**: Select the instance, and in the viewport, scale the Box Collision component to cover the desired trigger area in front of the door.
3. **Press Play**: Walk toward the door. It should slide open as you approach and close as you move away.

4.4.6.6 Common Variations

Rotating door (hinged door): Instead of Set Relative Location, use **Set Relative Rotation**. Connect the multiply result to the **Z** component of the split rotation vector. This rotates the door around its pivot point.

Horizontal slide: Connect the multiply result to the **X** or **Y** component of the split location vector instead of Z.

Multiple moving pieces: Add multiple Set Relative Location nodes (one per moving component) connected to the same Timeline Update output.

One-way door: Remove the End Overlap event entirely. The door opens but stays open.

Delay before closing: After the Timeline finishes playing forward, add a Delay node before calling Reverse.

4.4.6.7 Using Sequencer Instead

To achieve the same result with Sequencer:

1. Create a Level Sequence asset in the Content Browser
2. Add your door actor to the Sequencer and keyframe its Transform track
3. In your Blueprint, add a **Level Sequence Player** component
4. Replace the Timeline Play/Reverse calls with Level Sequence Player **Play** and **Reverse** nodes
5. The trigger logic remains identical

Sequencer provides more flexibility for adjusting the animation visually without reopening the Blueprint.

4.4.6.8 Troubleshooting

"Door doesn't move when triggered"

- Verify the Timeline is playing: Add a Print String after "Play From Start" to confirm execution reaches it
- Check the Update pin is connected to Set Relative Location
- Ensure you're modifying the correct component (DoorPiece, not the root or frame)

"Door moves in wrong direction or axis"

- Check which vector component (X, Y, or Z) you're driving with the multiply output
- Try inverting the multiply value (e.g., use -200 instead of 200) to reverse direction

"Door doesn't trigger"

- Verify "Generate Overlap Events" is enabled on the Box Collision component
- Check the Box Collision's collision preset (should overlap Pawn)
- Confirm the Cast to Character succeeds (the player is a Character)

"Door moves too far or not far enough"

- Adjust the multiply value: higher = more movement, lower = less movement
- The multiply value is in Unreal units (centimeters)

"Animation feels too fast/slow or jerky"

- Change the Timeline length (longer = slower animation)
- Adjust the curve type on keyframes (ease in/out for smoother motion)

"Door jumps to wrong position or animates from wrong starting point"

- This often happens when the door mesh has a non-zero initial relative position and your Timeline animation assumes it starts from zero
- **Solution**: Use a Scene Component wrapper pattern:
  1. Add an empty Scene Component as the parent of your door mesh
  2. Zero out the door mesh's relative position (set it to 0,0,0) first
  3. Now position the Scene Component where you want the door in the level—you'll see the door mesh move with it, providing visual feedback
  4. Your Timeline animation now works from zero, and the Scene Component provides the world-space offset
- This pattern keeps animation logic simple while allowing flexible positioning

4.4.7 Blueprint Variables and References

The door example above demonstrates Timeline animation and overlap events, but to create truly interactive systems, you need a way to store and manage state. Does the door stay locked until a switch is pressed? Has the player already triggered this checkpoint? Which specific door should this button control? These questions require **variables** and **references**—fundamental concepts that enable Blueprints to remember information and communicate with each other.

4.4.7.1 What Are Variables?

A variable is a named container that stores a piece of information during gameplay. Think of it as a labeled box where you can put data, check what's inside, and change the contents as needed.

Reading a variable means checking its current value—"Is the door locked?" **Writing** (or setting) a variable means changing its value—"Set the door to unlocked."

Variables in Blueprints persist while the game runs. If you set a door to unlocked, it stays unlocked until something explicitly locks it again or the level reloads.

4.4.7.2 Common Variable Types

Blueprint variables have specific **types** that determine what kind of information they can hold:

- **Boolean**: True or false. Perfect for on/off states like "IsDoorLocked" or "HasPlayerEnteredArea."
- **Integer**: Whole numbers (0, 1, 2, 100, -5). Used for counts like "CurrentCheckpoint" or "EnemiesDefeated."
- **Float**: Numbers with decimal points (3.14, 0.5, 100.0). Used for health values, timers, or any measurement needing precision.
- **String**: Text like "Welcome Player" or "KeyCardBlue." Useful for names, messages, or identifiers.
- **Vector**: 3D position (X, Y, Z coordinates). Stores locations in 3D space.
- **Rotator**: 3D rotation (Pitch, Yaw, Roll angles). Stores orientations.

For interactive triggers and state management, Boolean and Integer types are most common. A pressure plate might use a Boolean "IsActivated," while a multi-step puzzle might use an Integer "CurrentStep."

4.4.7.3 Creating Variables in Blueprints

Variables are created in the **My Blueprint** panel:

1. In the Blueprint editor, find the **Variables** section in the My Blueprint panel (typically left side)
2. Click the **+ Variable** button
3. Name your variable descriptively (e.g., "IsDoorLocked" not "Var1")
4. Select the variable type in the **Details panel** (Boolean, Integer, etc.)
5. Set the **default value**—the initial state when the Blueprint spawns

Once created, the variable appears in your variables list and can be dragged into the Event Graph.

4.4.7.4 Using Variables in Event Graphs

To use a variable in your Blueprint logic, drag it from the Variables list into the Event Graph. You'll be prompted to choose:

- **Get**: Read the current value without changing it. Use this to check state in conditions.
- **Set**: Change the value. Use this to update state when events occur.

A **Get** node outputs the variable's current value—you might connect it to a Branch node's condition to check "if door is locked." A **Set** node has an input where you specify the new value—you might connect this to an overlap event to mark "checkpoint reached = true."

Variables are what make your interactive systems remember state between events. Without variables, the door wouldn't know it was unlocked, and the switch wouldn't know it had been pressed.

4.4.7.5 What Are References?

Variables let one Blueprint remember its own state, but what if a floor switch needs to unlock a door? That requires a **reference**—a variable whose type is another Blueprint class. This allows one Blueprint to access and modify another Blueprint's variables or call its functions.

In the upcoming example, you'll create a switch Blueprint that holds a reference to a specific door Blueprint. When the player steps on the switch, it uses that reference to tell the door "set your IsDoorLocked variable to false."

References are set up similarly to other variables, but their type is a Blueprint class (like "Door" or "Light") instead of Boolean or Integer. Once you place both Blueprints in your level, you manually assign which specific door instance this switch controls via the Details panel.

4.4.7.6 Public vs. Private Variables

By default, variables are **private**—only the Blueprint that owns them can access them. To allow other Blueprints to read or change a variable through a reference, make it **public** by clicking the eye icon next to the variable in the My Blueprint panel. The eye icon turning solid indicates the variable is now **Instance Editable**, meaning:

1. Other Blueprints with a reference can access it
2. You can set its value per-instance in the Details panel when placing the Blueprint in a level

The upcoming practical example demonstrates all these concepts in action—creating variables, using Get/Set nodes, establishing references between Blueprints, and building interactive trigger systems that maintain state.

4.4.8 Practical Implementation: Switch Controlling Door

Building on the animated door from the previous section, let's add interactivity through variables and references. You'll create a floor switch that unlocks the door when stepped on—a fundamental pattern for triggers, pressure plates, buttons, and any mechanism where one object controls another's state.

YouTube Video

Building a Switch with Variables and References
Step-by-step tutorial demonstrating Blueprint variables and references by building a floor switch that controls a door's locked state. This video covers Boolean variables, Branch nodes for conditional logic, making variables public, and establishing references between Blueprints for inter-object communication.
Watch at: https://www.youtube.com/watch?v=01dEzec8bmo&t=s

This example extends the door Blueprint from the previous section and introduces a new switch Blueprint that controls it.

4.4.8.1 Modifying the Door Blueprint

First, add state management to your existing door:

1. **Add IsDoorLocked variable**:
    - Open your Door Blueprint from the previous example
    - In the My Blueprint panel, click + **Variable**
    - Name it **IsDoorLocked**
    - In the Details panel, set variable type to **Boolean**
    - Set the default value to **True** (door starts locked)
    - Click the **eye icon** to make it **public** (Instance Editable)
2. **Add locking logic with Branch nodes**:
    - In the Event Graph, find where your overlap events trigger the Timeline (Play From Start)
    - Before the Timeline node, add a **Branch** node
    - Drag the **IsDoorLocked** variable into the graph and choose **Get**
    - Connect the Get node's output to the Branch's **Condition** input
    - Connect the **False** branch output to the Timeline's Play From Start (door opens only if unlocked)
    - The **True** branch does nothing (door stays closed if locked)

- Repeat for the close logic on End Overlap

This conditional check ensures the Timeline only plays when the door is unlocked. Without it, overlap events would always trigger the door regardless of lock state.

3. **Optional - Add status display**:
    - Add a **Text Render** component to your door for visual feedback
    - In Event Graph, use **Event Tick** with a Branch to check IsDoorLocked
    - If True: Set Text to "Locked"
    - If False: Set Text to "Unlocked"
    - This constantly updates the display based on current state

Note: Event Tick runs every frame and can impact performance. For a production project, update the text only when the lock state changes rather than every frame. For learning purposes, this approach clearly demonstrates continuous state checking.

4.4.8.2 Creating the Switch Blueprint

Now create the floor switch that controls the door:

1. **Create new Blueprint Actor**:
    - In Content Browser, create Blueprint Class → Actor
    - Name it **FloorSwitch**
2. **Build visual components**:
    - Add Static Mesh components for the switch platform (e.g., cylinders for base and button)
    - Add a **Box Collision** component named **SwitchCollider**
    - Position and scale the collision to cover the switch area
3. **Add door reference variable**:
    - Click + **Variable**, name it **MyDoor**
    - In Details panel, set variable type to **object reference → Door** (your door Blueprint class)
    - Make it **public** (click eye icon) so you can assign specific door instances
4. **Add switch trigger logic**:
    - Select **SwitchCollider** component
    - Right-click → Add Event → On Component Begin Overlap
    - From the overlap event, add a **Cast to Character** node to verify it's the player

- From successful cast, drag out **MyDoor** reference and choose **Get**
- From the MyDoor output pin, search for "Set Is Door Locked"
- Connect the execution flow and set the Boolean value to **False** (unlock)
- Optional: Add **Play Sound at Location** for audio feedback

The key here is the **Set** node—it modifies a variable on a different Blueprint through the reference. The switch reaches into the door's variables and changes its locked state.

4.4.8.3 Connecting Switch to Door in the Level

The reference variable creates the connection, but you must assign which door instance:

1. Place your **Door** Blueprint in the level
2. Place your **FloorSwitch** Blueprint in front of the door
3. Select the **FloorSwitch** instance
4. In the **Details panel**, find the **MyDoor** variable
5. Click the dropdown and select the specific Door instance from your level

This manual assignment lets you create multiple switch-door pairs with different connections. One switch unlocks Door A, another unlocks Door B—the Blueprint logic is reusable, the specific relationships are configured per-instance.

4.4.8.4 Testing Your Switch

1. Press Play
2. Walk toward the door—it should remain closed (locked)
3. Step on the switch—you should hear the click sound
4. Return to the door—it should now open when you approach (unlocked)

4.4.8.5 Common Variations

Temporary unlock: Add a **Timer** after setting IsDoorLocked to False. After 5 seconds, set it back to True.

Toggle switch: Instead of setting to False, add a Get → NOT Boolean → Set pattern to invert the current state each time.

Multiple switches required: Add an Integer "SwitchesActivated" to the door. Each switch increments it. Door only unlocks when SwitchesActivated >= RequiredCount.

One-time trigger: Add a Boolean "HasBeenActivated" to the switch. Check it in the overlap event—if True, do nothing. If False, unlock door and set HasBeenActivated to True.

4.4.8.6 Troubleshooting

"Switch doesn't unlock door"

- Verify MyDoor reference is assigned in the Details panel (not None)
- Check that IsDoorLocked is public (eye icon solid) on the door Blueprint
- Confirm the Cast to Character succeeds—print a debug string to verify

"Door unlocks but won't open"

- Check the Branch logic in the door—False branch should lead to Timeline Play
- Verify IsDoorLocked is actually set to False by the switch (add a Print String showing the value)

"Switch triggers for objects other than player"

- Ensure you're using Cast to Character and only continuing execution on successful cast
- Check collision settings on SwitchCollider (should overlap Pawn/Character)

"Multiple switches all control the same door"

- This is correct if you assigned the same door reference to all switches
- To have switches control different doors, assign different door instances to each switch's MyDoor variable

This pattern—trigger volume, Boolean variable, Branch node, Blueprint reference—forms the foundation for most interactive mechanisms in Unreal. Pressure plates, buttons, levers, and puzzle elements all build on these concepts.

4.5 From Physics to Interaction: Looking Ahead

The foundational concepts of physics simulations, collision detection, and event-driven programming we've explored in this chapter form the basis for creating rich, interactive experiences in XR. In this final section, we'll look ahead to how these concepts enable more complex interactions and mechanisms, which we'll explore in depth in later chapters.

4.5.1 Bridging Physics and Interaction

The physical properties and behaviors we've discussed don't exist in isolation; they serve as the building blocks for user interactions in XR environments. For example:

1. Physics simulations allow objects to behave realistically when manipulated
2. Collision detection enables precise interaction between the user and virtual objects
3. Event-driven programming ties user actions to object responses

These elements combine to create a sense of presence and immersion that is crucial to effective XR experiences.

4.5.2 The Power of Grabbing in VR

One of the most fundamental interactions in VR is the ability to grab and manipulate objects. While we'll delve into implementation details in a later chapter, it's worth noting how this interaction ties together the concepts we've covered:

- Physics determines how objects move when grabbed and released
- Collision detection recognizes when a user's hand is near a grabbable object
- Events trigger the grabbing action and subsequent object behavior

Grabbing mechanics demonstrate the power of combining these elements to create intuitive, immersive interactions that mirror real-world experiences.

4.5.3 Complex Mechanisms and Environmental Interactions

Looking ahead, we'll explore how to create more complex interactive systems:

1. **Levers and Buttons**: Using physics and events to create interactive control mechanisms
2. **Dynamic Environments**: Creating responsive environments that change based on user actions
3. **Multi-step Interactions**: Designing puzzles or tasks that require a series of physics-based interactions

These advanced interactions build directly on the foundations laid in this chapter.

4.5.4 The Role of AI in Interactive Environments

Artificial intelligence can significantly enhance the interactivity of XR environments through AI-controlled characters, intelligent objects, and dynamic environments that evolve based on physics simulations and AI decision-making.

For comprehensive coverage of AI applications in XR environments, including intelligent characters, adaptive behaviors, and dynamic content generation, see Chapter 8.

4.5.5 Looking Forward

In the coming chapters, we'll delve deeper into:

1. Specific interaction techniques like grabbing, pointing, and locomotion
2. User interface design for XR environments
3. Advanced interaction paradigms that build on physics and events
4. The integration of AI to create more dynamic and responsive experiences

Each of these topics will build upon the fundamental concepts of physics, collisions, and events that we've covered in this chapter.

4.5.6 Conclusion

The physics simulations, collision systems, and event-driven programming we've explored form the foundation of interactive XR environments. As we move forward, we'll see how these elements combine with more advanced concepts to create truly immersive and engaging XR experiences. The journey from basic physics to complex, intelligent interactions is what makes XR development so exciting and full of potential.

4.6 Further Reading

Chapter 4 explored the creation of dynamic and interactive virtual environments, focusing on physics simulations, collision detection, and event-driven programming in XR. We delved into how these elements contribute to creating more realistic and engaging virtual worlds. To further your understanding of these topics and their practical applications, consider the following resources:

4.6.1 Additional Resources

- Unreal Engine Physics Documentation: https://dev.epicgames.com/documentation/en-us/unreal-engine/physics-in-unreal-engine
  - Detailed guides on implementing physics in Unreal Engine.

5 Spatial Interaction Design

5.1 Input Methods and Controllers in XR

Virtual Reality (VR) and other XR technologies offer unique ways to interact with digital environments. This section explores the various input methods and controllers used in XR, with a focus on VR interaction techniques.

5.1.1 VR Controllers and Hand Tracking

Modern VR systems typically use handheld controllers or hand tracking systems to allow users to interact with virtual objects. These input methods provide a more natural and intuitive way to manipulate the virtual environment compared to traditional input devices like keyboards and mice.

5.1.1.1 VR Controllers

VR controllers are handheld devices that allow users to interact with virtual objects. They typically include:

- Buttons for various actions
- Analog sticks or touchpads for movement and menu navigation
- Triggers for grabbing or selecting objects
- Haptic feedback for enhanced immersion

Many VR systems, such as the Oculus Quest, come with two controllers - one for each hand. This allows for more natural, two-handed interactions in the virtual space.

5.1.1.2 Hand Tracking

Some VR systems, like the Oculus Quest, also offer hand tracking capabilities. This allows users to interact with the virtual environment using their bare hands, without the need for controllers. While this can provide a more intuitive interaction in some cases, it may lack the precision and haptic feedback of physical controllers.

5.1.2 Basic VR Interactions

VR systems typically support several basic types of interactions:

1. **Pointing and Selection**: Users can point at objects in the virtual environment and select them, often using a laser pointer-like interface.
2. **Grabbing and Manipulation**: Users can reach out and grab virtual objects, manipulating them as they would in the real world.
3. **UI Interaction**: Users can interact with 2D or 3D user interfaces, pressing buttons or manipulating sliders and other UI elements.
4. **Locomotion**: Various methods for moving around in the virtual space, which we'll explore in more detail in section 4.2.

5.1.3 Implementing Basic Interactions in Unreal Engine

Unreal Engine provides robust VR templates that offer a foundation for developing immersive VR experiences. These templates are included in the MyExercises template and provide essential functionalities for VR interaction.

5.1.3.1 Key Features of VR Templates

1. **Realistic Hand and Head Positioning**: The VR templates ensure that hands and head are positioned sensibly relative to the tracking system. This creates a more natural and intuitive VR experience.

When you're actually using this in VR, these hands will be your hands, so you can use them as you would expect to in VR. The tracking system ensures your head and hands are positioned at the correct height relative to the floor and surroundings.

2. **Hand Interaction Capabilities**: Users can interact with the virtual environment using their hands in several ways:

- Poking or pushing objects
- Picking up items
- Dropping or throwing objects

These interactions are made possible through the implementation of specific interfaces on actors within the virtual environment.

5.1.3.2 Using VR Templates Without VR Hardware

One of the significant advantages of these templates is their usability even without VR hardware. This feature allows developers to design and test VR interactions using standard input devices.

5.1.3.2.1 Hand Interactions Without VR

1. **Poking and Grabbing**: Users can still use virtual hands to interact with objects.
2. **Throwing**: While more challenging without VR controllers, it's still possible to throw objects.

5.1.3.2.2 Keyboard Controls

The templates include keyboard controls to simulate VR hand movements: - Press 'R' to reach forward - Press 'T' to turn the hand

You can press 'R' on the keyboard to reach forward with one of the hands, and press 'T' to perform a turn. I encourage you to check the implementation of these controls and feel free to imitate that approach when coding different kinds of motions you want to explore and use in your experiments.

These controls are implemented in the VRCapablePawn blueprint, specifically in the MotionControllerEvents graph.

5.1.3.2.3 Mouse Controls

- Use the Left mouse button to grab with the right hand

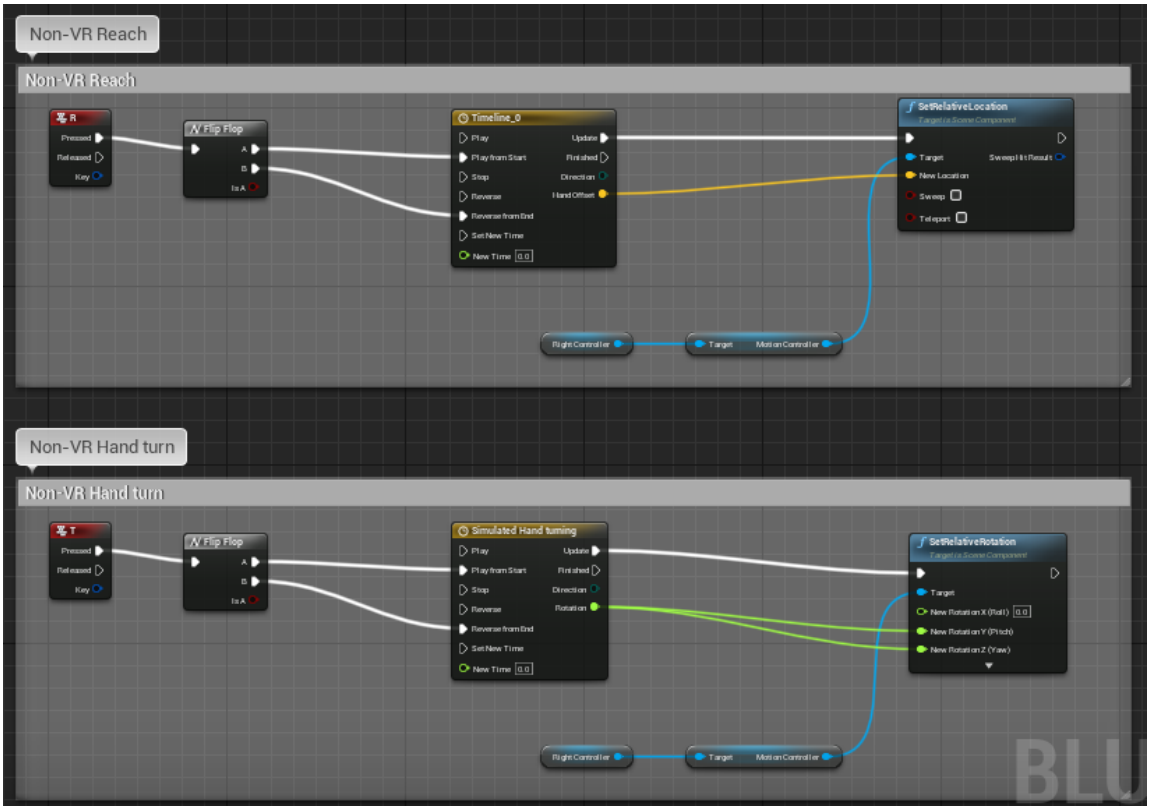


Figure 5.1: Unreal Engine Non-VR Hands

5.1.4 Implementing Grab Functionality with GrabComponent

To simplify object interaction in your VR projects, you can utilize the **GrabComponent** provided in the exercise template. This component is much simpler to use than methods from previous years and allows for straightforward implementation of grabbing mechanics.

Key Features of GrabComponent:

- **Easy Attachment/Detachment**: Attach or detach actors from the grabbing component, effectively simulating the action of picking up or dropping objects with a "hand."
- **Physics Simulation Toggle**: Control physics simulation to pick up or drop physics-enabled objects.
- **Movement Without Physics**: Move objects through space without relying on physics, providing more control over their behavior.

To use the GrabComponent, simply add it to component list of the actor you want to be able to grab, keeping the checklist below in mind.

5.1.5 Checklist for Implementing Grabbing Mechanics

To ensure smooth functionality when using the **GrabComponent**, follow this checklist:

1. **Set the Object to Movable**
    - Ensure that the object you want to grab is marked as **Movable** in its settings. Static objects cannot be moved during gameplay.
    - Confirm that the object has appropriate **Collision** settings to interact with the grabbing component.

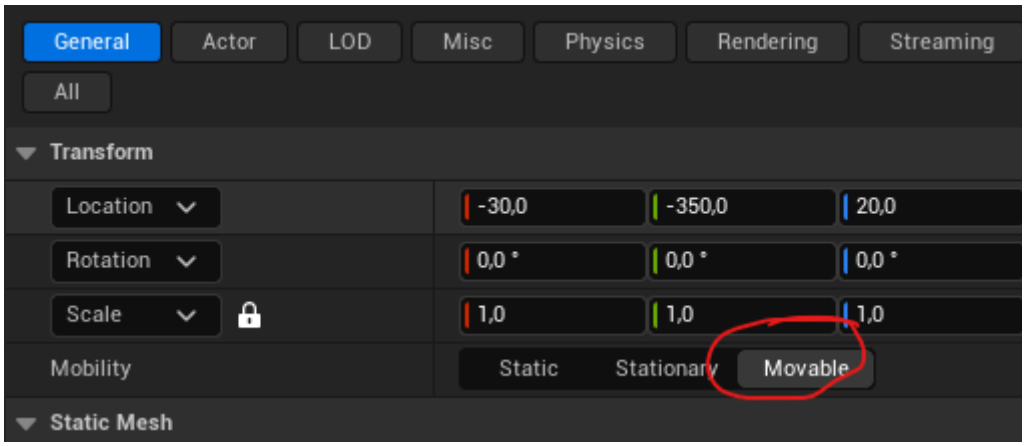


Figure 5.2: Setting Object to Movable

2. **Enable Overlap Events**
    - Activate **Generates Overlap Events** on the object. This allows the system to detect when the grabbing "hand" overlaps with the object, which is essential for initiating the grab action.
3. **Enable Physics Simulation (If Required)**
    - If you want the object to behave according to physics when dropped (e.g., fall due to gravity), enable **Simulate Physics** on the object.
    - This setting allows the object to interact naturally with the environment when not held.

4. **Verify Component Hierarchy in Complex Blueprints**
    - For objects with complex blueprints or multiple components, check the component hierarchy.
    - Ensure that the **GrabComponent** acts on the parent component so that all child components follow correctly during movement.

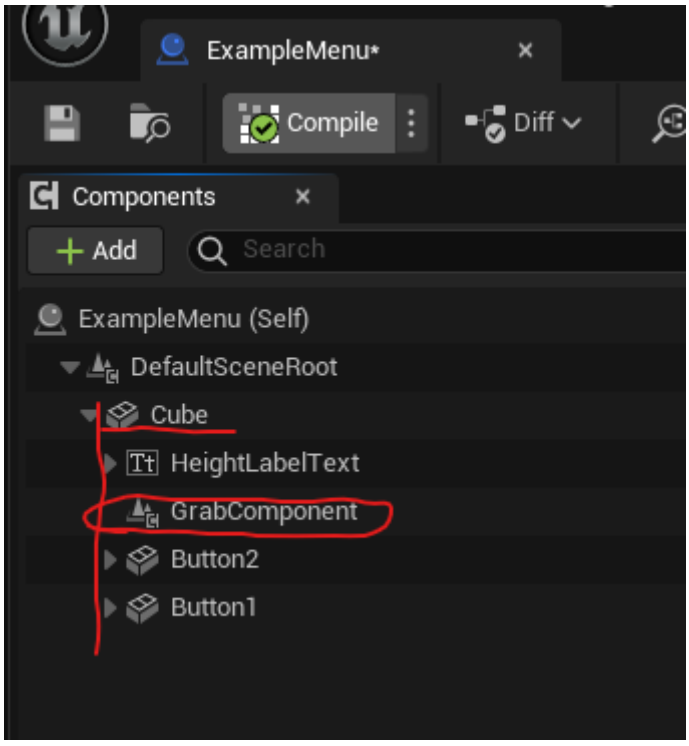


Figure 5.3: Component Hierarchy in Blueprint

By carefully following these steps, you can effectively implement grabbing mechanics in your VR application, providing users with an intuitive and responsive experience.

5.2 Constrained Manipulation: Levers, Switches, and Sliders

While grabbing freely movable objects with GrabComponent works well for items you pick up and carry, many VR interactions require **constrained manipulation**—objects that rotate around a pivot, slide along a track, or toggle between positions. Think of valve wheels, light switches, drawer handles, or cockpit controls. These require a different

approach: continuously tracking hand movement while manually constraining the object's transform.

5.2.1 The Manual Tracking Approach

Unlike free object grabbing, constrained manipulation doesn't use attachment or physics simulation. Instead, you:

1. **Detect grab**: Use overlap events and grip button input (similar to GrabComponent)
2. **Track continuously**: Every frame while grip is held, read the hand's position/rotation
3. **Calculate constrained transform**: Project hand movement onto the allowed axis or rotation, clamp to min/max limits
4. **Update manually**: Set the object's transform directly using `Set Relative Location` or `Set Relative Rotation`
5. **Release**: When grip is released, stop tracking

This manual approach gives you precise control over exactly how the object moves and avoids the complexity of physics constraints, which can be finicky and unpredictable in VR.

5.2.2 Common Constrained Interaction Types

Rotational Levers (valves, dials, door handles): - Object rotates around a pivot point (single axis rotation) - Hand rotation drives object rotation within min/max angle limits - Maps to normalized 0-1 value (e.g., 0° to 270° → 0.0 to 1.0)

Linear Sliders (throttles, faders, drawers): - Object moves along a single axis (X, Y, or Z) - Hand position drives object position within min/max distance limits - Maps to normalized 0-1 value based on position along track

Multi-Position Switches (toggle switches, gear shifts): - Object snaps to discrete positions - Hand position determines which snap point is closest - On release, object jumps to nearest position with haptic/audio feedback

5.2.3 Blueprint Examples

For complete Blueprint implementations of these patterns, see:

- **Lever/Rotational Control**: https://blueprintue.com/blueprint/4i4x60m3/

- **Slider/Linear Control**: https://blueprintue.com/blueprint/2m1xqbkj/

These examples demonstrate the full event flow from grip detection through continuous tracking to release, showing how to handle the constraint math in Blueprint nodes.

5.2.4 Practical Implementation: Rotational Lever

Let's build a simple valve wheel that rotates when grabbed. This pattern applies to door handles, steering wheels, dials, and any rotating control.

5.2.4.1 Setting Up the Lever Blueprint

1. **Create Blueprint Actor**:
    - Content Browser → Blueprint Class → Actor
    - Name it "RotationalLever"
2. **Add components**:
    - **Static Mesh** for the lever handle (the part user grabs)
    - **Scene Component** as root (optional, for easier positioning)
    - **Sphere Collision** component overlapping the grabbable area
3. **Configure collision**:
    - Sphere Collision: Enable "Generate Overlap Events"
    - Set to overlap with Pawn (so hand controller triggers it)

5.2.4.2 Adding Variables

In the My Blueprint panel, add these variables:

- **bIsGrabbed** (Boolean): Tracks whether lever is currently held
- **MinAngle** (Float): Minimum rotation angle (e.g., 0)
- **MaxAngle** (Float): Maximum rotation angle (e.g., 270)
- **CurrentValue** (Float): Normalized value 0.0 to 1.0
- **GrabbingHand** (Object Reference → MotionControllerComponent): Reference to which hand is holding

Make MinAngle and MaxAngle public (Instance Editable) so you can configure per-instance.

5.2.4.3 Implementing Grab Detection

1. **Add overlap event**:
    - Select Sphere Collision component
    - Right-click → Add Event → On Component Begin Overlap
2. **Add grip input event**:
    - In Event Graph, add input event for grip button
    - For Oculus/Quest: "MotionController (Right) Grip1 Axis"
    - Use Branch to check if axis value > 0.5 (grip pressed)
3. **Connect grab logic**:
    - When overlap occurs AND grip pressed:
    - Set **bIsGrabbed** to True
    - Store reference to overlapping actor (the hand) in **GrabbingHand**

5.2.4.4 Implementing Continuous Tracking

This is the key part—while held, update every frame:

1. **Add Event Tick**:
    - This runs every frame
    - First node: Branch checking **bIsGrabbed**
2. **Get hand rotation**:
    - From **GrabbingHand** reference → Get World Rotation
    - Break Rotator to get individual components (Roll, Pitch, Yaw)
3. **Calculate constrained rotation**:
    - Decide which rotator component drives your lever (usually Yaw or Roll depending on axis)
    - Use **Clamp (Float)** node: clamp hand rotation between MinAngle and MaxAngle
    - This gives you the constrained angle
4. **Set lever rotation**:
    - Make Rotator from your constrained angle (put it in the right component: X for Roll, Y for Pitch, Z for Yaw)
    - **Set Relative Rotation** on lever mesh with this rotator

5. **Calculate normalized value**:
    - Subtract MinAngle from constrained angle
    - Divide by (MaxAngle - MinAngle)
    - Store in **CurrentValue** variable (now 0.0 to 1.0)

Important: Only do this tracking on Event Tick when **bIsGrabbed** is True. This keeps it efficient—no calculations when lever isn't held.

5.2.4.5 Implementing Release

1. **Add grip release event**:
    - Same grip axis input, but Branch for value < 0.5 (released)
2. **Connect release logic**:
    - Set **bIsGrabbed** to False
    - Clear **GrabbingHand** reference (set to None)
    - Optional: Broadcast the final **CurrentValue** via Event Dispatcher for other systems

5.2.4.6 Using the Lever Value

The **CurrentValue** variable (0.0 to 1.0) can drive other systems:

Method 1: Direct access - Other Blueprints can get a reference to your lever - Read CurrentValue directly (make it public)

Method 2: Event Dispatcher - Add Event Dispatcher "OnValueChanged" - Call it whenever CurrentValue updates (or on release) - Other Blueprints bind to this event

Example uses: - Lerp a light's intensity: `Light Intensity = Lerp(0, 5000, CurrentValue)` - Control particle spawn rate: `Spawn Rate = Lerp(0, 100, CurrentValue)` - Drive animation: `Set Playback Position = CurrentValue` on a Timeline

5.2.4.7 Common Variations

Linear Slider (throttle, drawer): - Same structure, different math - Track hand **position** instead of rotation - Project hand position onto slider axis using **Vector Projection** - Clamp to min/max distance - Use **Set Relative Location** instead of rotation

Multi-Position Switch: - Define array of snap positions (e.g., [-0.1, 0.0, 0.1] for 3-position switch) - Track hand position while held (same as slider) - On **release**: find closest snap position, set object to that exact position - Play click sound and haptic pulse when snapping

Two-Handed Wheel (steering wheel): - Track both hands if both gripping - Calculate rotation from vector between hands - Use midpoint of hands as reference for rotation calculation

5.2.4.8 Troubleshooting

"Lever jumps to wrong angle when grabbed" - Calculate initial grab offset: store difference between hand angle and lever angle at grab moment - Apply this offset during tracking to maintain natural feel

"Lever rotation feels jittery" - Add smoothing: Lerp from current rotation toward target rotation - `New Rotation = Lerp(Current, Target, 0.3)` for smooth following

"Lever doesn't track hand rotation" - Verify you're reading the correct rotator component (Roll/Pitch/Yaw) - Check lever's pivot point—rotation should be around correct axis

"Other objects can grab the lever" - Add Cast to MotionControllerComponent in overlap event - Only set bIsGrabbed if overlapping actor is actually a hand controller

5.2.4.9 Blueprint References

For complete working examples showing all the node connections:

- **Rotational lever**: https://blueprintue.com/blueprint/4i4x60m3/
- **Linear slider**: https://blueprintue.com/blueprint/2m1xqbkj/

These show the full Event Tick tracking loop, constraint math, and proper release handling.

5.2.5 Integration with Haptics

Consider adding haptic feedback for better physicality (see Section 5.5 for details):

- **Threshold crossings**: Pulse when CurrentValue passes 0.25, 0.5, 0.75
- **Min/max limits**: Stronger pulse when reaching ends of range
- **Snap positions**: Strong pulse when switch snaps to position

- **Continuous feedback**: Light pulse proportional to movement speed while dragging

Haptic feedback makes constrained manipulation feel more physical and helps users understand the control's range without looking at it.

5.2.6 Conclusion

Understanding and implementing these basic interaction methods is crucial for creating immersive and intuitive XR experiences. As you develop your projects, consider how these interactions can be used to create engaging and natural user experiences in your virtual environments.

For more detailed information on VR interaction in Unreal Engine, refer to the Unreal Engine VR Development Documentation.

5.3 Spatial Platform Capabilities (2025)

Contemporary headsets and glasses ship with increasingly rich spatial understanding out of the box. Designers can now assume that most platforms offer at least anchors, surface reconstruction, and semantic understanding—with notable nuances by vendor.

5.3.1 Core Capability Checklist

- **Anchors & Persistence**: Anchor systems let virtual objects stay attached to real-world positions. Niantic's 2025 Spatial SDK update extends centimeter-accurate Visual Positioning System (VPS) anchors from phones to Quest 3 headsets, so a task board you pin in a lobby remains in place across sessions and devices.(Niantic Labs 2024b)
- **Meshing & Scene Understanding**: Live meshing now runs locally on consumer headsets. Niantic demonstrates near-field meshes for living rooms and lobby-scale reconstructions, while Meta's Depth API powers instant placement without full scans.(Niantic Labs 2024b; Lang 2024)
- **Semantics & Object Labels**: Semantic segmentation (walls, floors, furniture) feeds more context into your UX logic—trigger hand-off guides only when a "table" is detected or scale UI to fit actual wall dimensions.
- **Occlusion & Depth**: Depth sensors or reconstructed meshes allow virtual content to hide behind real objects. This is essential for believable MR portals, spatial UI, and colocation-heavy multiplayer.

Friction reducers to design around

- **Instant placement** (Meta Quest SDK v71): Drop objects directly on detected surfaces using the Depth API, reducing the onboarding flow from a 60-second scan to a single tap.
- **Keyboard cutouts**: Quest now supports passthrough around any Bluetooth keyboard, so productivity apps can expose physical peripherals without custom calibration.
- **Automatic colocation discovery**: Nearby Quest headsets can find each other over Bluetooth, allowing same-room multiplayer to start without room codes—pair this with shared anchors for rapid collaborative setup.

5.3.2 Planning for Cross-Device Deployments

Android XR's cross-device strategy and Niantic's shared SDK suggest a practical baseline.(Google LLC 2024b; Niantic Labs 2024b)

1. **Design with feature tiers**: Assume anchors + basic depth everywhere, with semantics and meshing as optional enhancements.
2. **Build shared scene graphs**: Use platform services (Niantic VPS, Meta Shared Spatial Anchors) to sync object placement across phones, standalone headsets, and future smart glasses.
3. **Prototype friction flows**: Test how quickly someone can place an object, join a colocated session, or reveal a keyboard. Small latency improvements drastically affect perceived polish.

Grounding design decisions in these capabilities keeps experiences portable across the full form-factor spectrum introduced in Chapter 2.

5.4 Locomotion Techniques in Virtual Reality

Locomotion in virtual reality (VR) presents unique challenges and opportunities. The ability to move within virtual spaces larger than the physical reality is crucial for creating immersive experiences. However, implementing movement in VR requires careful consideration to maintain user comfort and prevent motion sickness.

5.4.1 The Challenge: Motion Sickness

While locomotion is essential for immersive VR experiences, it presents a significant challenge: motion sickness. This issue arises from what is known as visual-vestibular conflict.

5.4.1.1 Visual-Vestibular Conflict

This conflict occurs when there's a mismatch between what the user sees in the VR headset and what their inner ear (vestibular system) senses. As

You see this environment that feels real and you see yourself moving there, but you don't feel it in your inner ears—the vestibular system that senses acceleration and helps with balance.

This discrepancy can lead to the body reacting as if something is wrong, potentially triggering nausea as a defense mechanism. One theory suggests that this reaction might be evolutionary, similar to the body's response to ingesting poison.

5.4.2 Individual Variation

Susceptibility to VR-induced motion sickness varies greatly among individuals. Some people may experience discomfort from merely watching a car ride on a large screen, while others can handle complex movements in VR without significant issues.

5.4.3 The Phenomenon of "VR Legs"

A common sentiment in the VR community is the concept of developing "VR legs" - the idea that users can acclimate to VR environments and reduce motion sickness over time. Porter and Robb (2019) explored this phenomenon, finding that while some users do indeed adapt, this is not universal.

You can, to a certain degree, develop what we call "VR legs" as you get used to using virtual reality. You can tolerate more of these kinds of motions over time, but this adaptation isn't true for everyone.

> The sentiment being that "some get sick, some don't, and some adapt," where some users have a very high natural resistance, others a low resistance, and the remainder possess a moderate resistance with the ability to increase their resistance over time. This increased resistance was known by the community as obtaining one's 'VR Legs,' which was described as being "like sealegs, but for VR." The idea being that:
>
> > "practice makes perfect, and VR can take some getting used to. Some have it easier, some have it a bit more difficult, but if you power through you should be able to get your VR legs after a while"
>
> With the understanding that this did not hold true for everyone because "some people [will still] get motion sickness, no matter how much they 'train' themselves."

Figure 5.4: About possible VR Legs adaptation, or not. Quote from Porter and Robb (2019).

5.4.4 Solutions to VR Locomotion Challenges

Developers have devised various solutions to address motion sickness in VR, each with its own advantages and limitations:

5.4.4.1 1. No Visual Motion (or Acceleration)

- **Teleportation/Dashing**: Users instantly move to a new location without showing the transition.
  - Reduces visual-vestibular conflict by eliminating perceived motion.
  - Most effective when avoiding acceleration visuals.

5.4.4.2 2. Reduced Visible Motion

- **Tunneling**: Narrows the field of view during movement.
  - Exploits the fact that we're most sensitive to motion in our peripheral vision.
- **Morphing**: Alters the world in ways that the brain doesn't interpret as typical movement.

5.4.4.3 3. Setting Expectations

- **Running in Place**: Encourages physical movement that aligns with virtual motion. If you're running in place while moving in VR, that physical action really helps the brain accept that the movement you're seeing is reasonable and makes sense.
- **Pulling the World**: Allows users to grab and move the virtual environment directly. This sets expectations to moving the world, not to you moving through the world.

5.4.4.4 4. Combining Approaches

Developers often combine these techniques, creating narratives or tools within the virtual world to explain and facilitate movement. This approach can help direct user attention and make locomotion feel more natural within the context of the experience.

5.4.5 Locomotion Options in Unreal Engine VR Templates

Unreal Engine provides several built-in locomotion options for VR experiences, designed to enhance user comfort and reduce motion sickness.

5.4.5.1 Teleportation with Parabolic Pointing

Teleportation is a popular VR movement technique that allows users to instantly transport to a new location. The Unreal Engine template implements this with parabolic pointing.

Key Features: - Uses a parabolic trajectory to determine teleport destination - Allows reaching higher positions - Limits teleportation range for better control

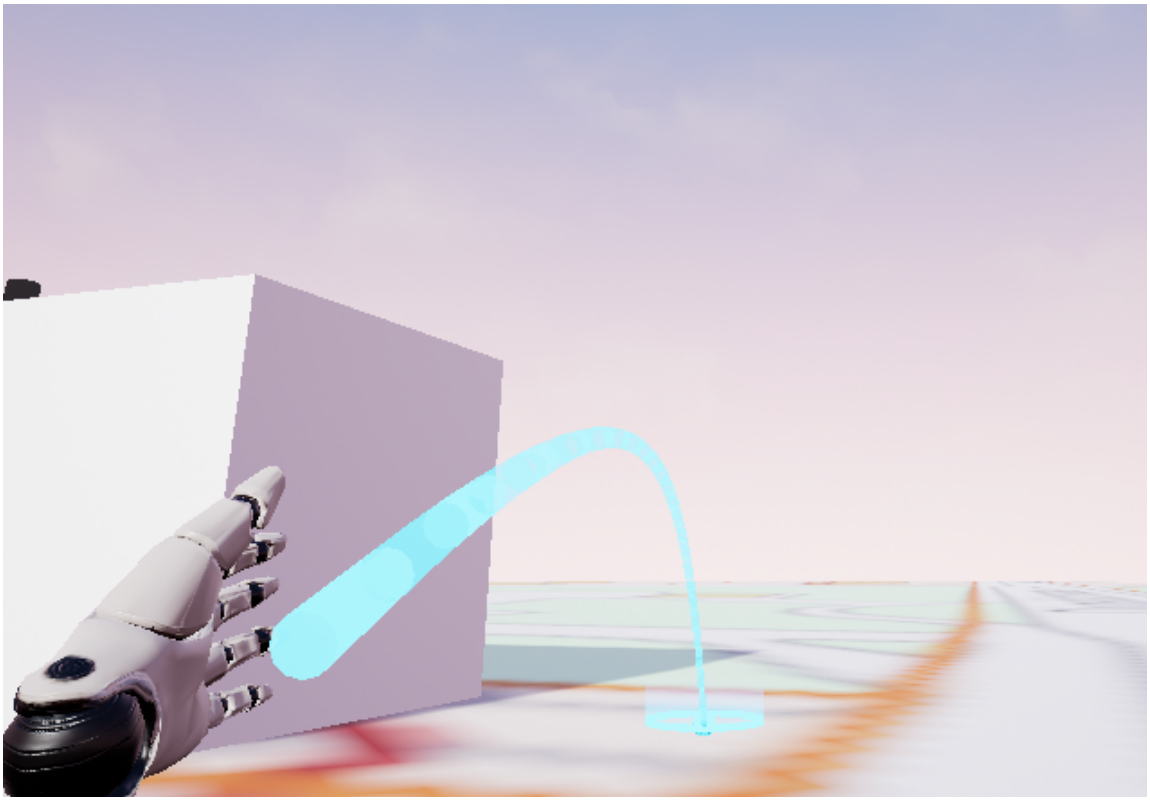


Figure 5.5: Visualization of parabolic teleportation trajectory.

5.4.5.2 Snap Turning

Snap turning is a technique to reduce motion sickness when rotating in VR.

Key Features: - Turns the view by 45 degrees in one quick motion - Can be pressed multiple times for larger rotations - Helps prevent disorientation caused by smooth rotation

5.4.5.3 Snap/Blink Movement

This technique allows for short, controlled movements in VR space.

Key Features: - Moves the user 1 meter forward or backward in one quick motion - Can be used multiple times for longer distances - Doesn't require pointing to a specific location each time

5.4.5.4 Quick Fade Transition

All locomotion techniques in the template use a quick fade to black and back during movement.

Purpose: - Helps the brain ignore the sudden change in position - Reduces the likelihood of motion sickness

Each of these locomotion techniques is implemented with a quick fade to black and back. This helps the brain ignore the movement because it becomes less aware of—or doesn't detect—the actual switch from one place to another when there's a brief blackout in between.

5.4.6 Implementing Teleportation in Exercises

For simple teleportation exercises, students can use a streamlined approach:

1. Check if the player enters a trigger box acting as a teleporter
2. Use the teleport blueprint node to move the player to a new location
3. Optionally, teleport to another level using the "Open Level" blueprint node

Tip for Targeting: Use the position of an actor as the teleport target for more dynamic teleportation.

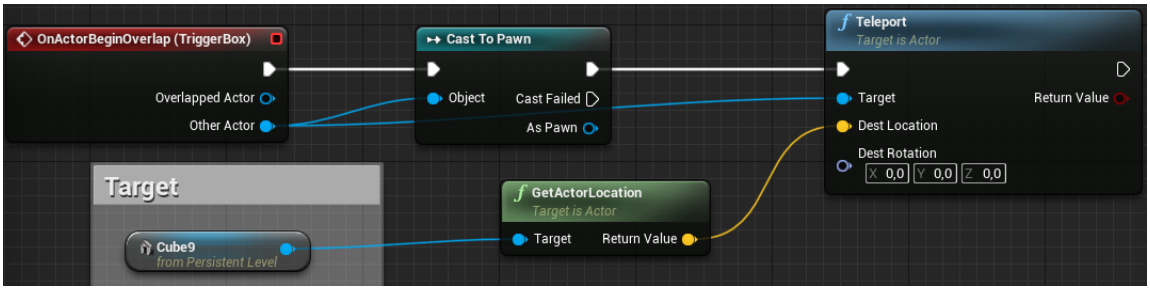


Figure 5.6: Example of using an actor's position as a teleport target.

5.4.7 Advanced Locomotion Techniques

For more advanced applications, researchers and developers have explored innovative locomotion techniques:

5.4.7.1 Redirected Walking and the Unlimited Corridor

Redirected walking is a technique that allows users to explore seemingly infinite virtual spaces within a limited physical area. This is achieved by subtly manipulating the user's perception of movement.

YouTube Video

Redirected Walking Unlimited Corridor Demo
Experience how users can walk infinitely in VR within a limited physical space using clever spatial manipulation techniques. The physical path curves while users perceive walking straight along an endless corridor, solving space constraints in room-scale VR.
Watch at: https://www.youtube.com/watch?v=THk92rev1VA&t=s

This is one of the more impressive recent developments I've encountered. By constructing this particular wall shape, you can fool users into thinking they're walking along an infinitely long straight wall when they're actually walking in a curve.

5.4.7.2 Galvanic Vestibular Stimulation

To address the issue of motion sickness in VR, researchers are exploring ways to directly stimulate the vestibular system, which is responsible for our sense of balance and spatial orientation.

YouTube Video

Galvanic Vestibular Stimulation for VR Motion
Learn about experimental technology that uses electrical stimulation of the inner ear to create sensations of movement and acceleration. This approach could potentially solve VR motion sickness by synchronizing vestibular perception with visual motion in virtual environments.
Watch at: https://www.youtube.com/watch?v=5Li_1xQV_Hs&t=s

This technique is called Galvanic Vestibular Stimulation (GVS), where you essentially apply controlled electrical signals to stimulate the vestibular system, making you feel as if you're accelerating and turning in different directions. This is a potential "holy grail" for solving VR motion issues, as the only suggestion that might completely remove it.

This technology, while still in research stages, could potentially solve one of the major challenges in VR by aligning the user's sense of movement with the visual input from the VR environment.

5.4.8 Conclusion

Locomotion in VR remains an active area of research and development. While various techniques have been developed to mitigate motion sickness and enhance user comfort, the choice of locomotion method often depends on the specific application and target audience. As VR technology continues to evolve, we can expect to see further innovations in this crucial aspect of virtual reality experiences.

For more information on locomotion in Unreal Engine, refer to the Unreal Engine VR Locomotion Documentation.

5.5 Designing User Interfaces for 3D Spaces

Creating effective user interfaces (UI) for 3D spaces in Extended Reality (XR) presents unique challenges and opportunities. This section explores the principles and techniques for designing UI elements that seamlessly integrate with virtual environments.

5.5.1 The Challenge of 2D UI in VR

Traditional 2D user interfaces do not translate well to virtual reality (VR) environments. There are two main issues:

1. **Stereo Effect Distortion**: Simply projecting a 2D interface onto the VR screens results in an incorrect stereo effect, making the UI difficult to perceive properly.
2. **Lack of Natural Interaction**: Without proper placement in 3D space, users cannot interact with the UI using natural body movements, which is a key aspect of VR experiences.

In short, showing ordinary UI overlays does not work in VR.

5.5.2 Unreal Engine's Solution: Placing UI on 3D Surfaces

To address these challenges, Unreal Engine adopts an approach of placing 2D interfaces on surfaces within the 3D environment. This solution involves creating a virtual screen that exists as part of the VR world, allowing for proper depth perception and intuitive interaction.

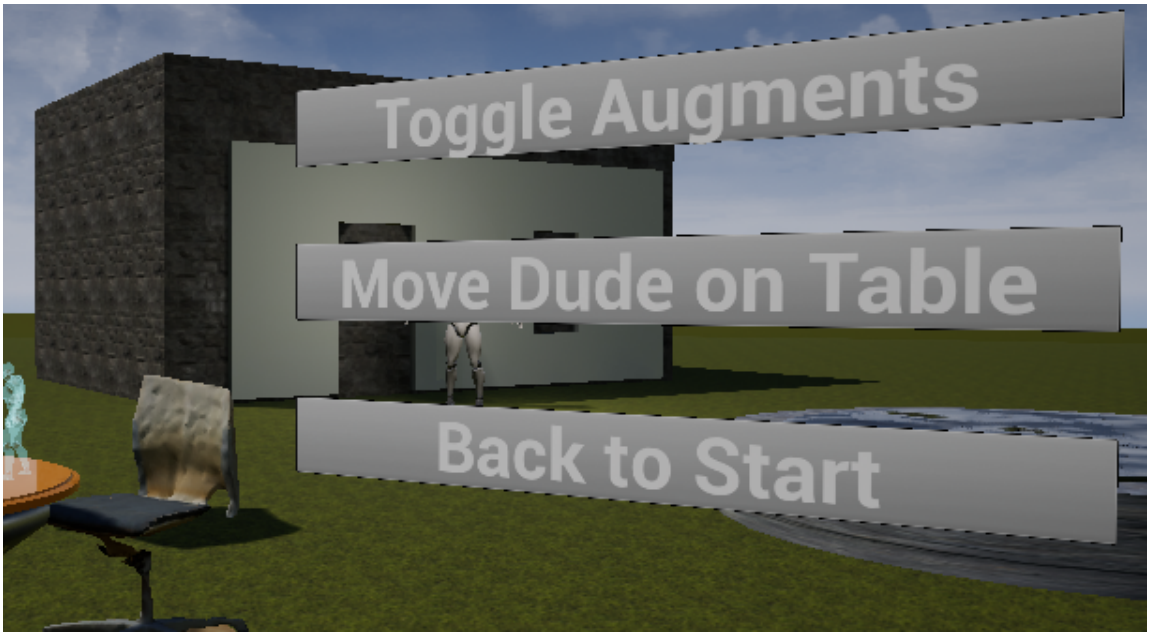


Figure 5.7: Unreal UI 3D Example

The image above demonstrates how a 2D interface can be integrated into a 3D VR environment, complete with hand controllers for interaction.

5.5.3 Required Components for 2D UI in VR

To implement a 2D user interface in VR using Unreal Engine, three key components are necessary:

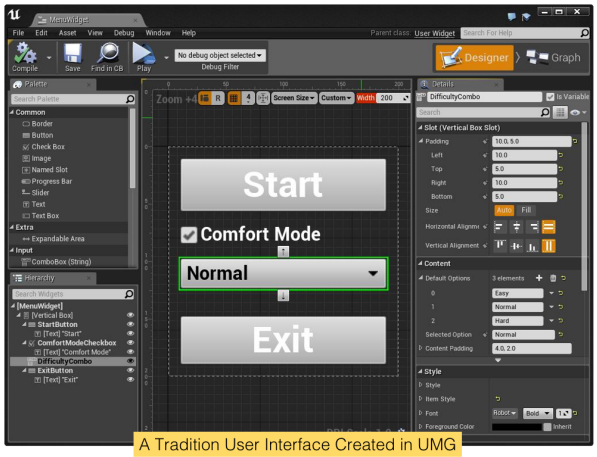
1. **Menu Actor**: This is a Blueprint actor that serves as the container for the 2D surface in 3D space. It allows you to position and manipulate the UI within the virtual environment.
2. **UMG Widget**: UMG (Unreal Motion Graphics) is Unreal Engine's system for creating 2D user interfaces. The UMG Widget is connected to the Menu Actor and contains the actual UI design.
3. **Widget Interaction Component**: This component is attached to the player's Pawn (usually the hand or controller) and acts as a pointer, enabling interaction with the 2D interface elements like buttons.

5.5.4 Creating UIs with UMG

UMG provides a familiar environment for designing 2D interfaces within Unreal Engine. It offers a range of common UI widgets and allows for hierarchical construction of interfaces.

Key features of UMG include:

- A variety of widgets common to 2D UIs
- Ability to build interfaces hierarchically (e.g., adding a text label as a child of a button)
- Visual editor for easy UI design



UMG 2D INTERFACE

You can use UMG UI Designer to create complex 2D user interfaces with a built-in palette of common widgets.

Source: **Unreal Engine VR Cookbook**

Figure 5.8: UMG Editor Example

For more detailed information on using UMG, refer to the UMG UI Designer Quick Start Guide.

5.5.5 Implementing the Menu Actor

The Menu Actor is crucial for placing your 2D interface in the 3D VR environment. Here's how to set it up:

1. Create a new Blueprint actor or extend an existing one.
2. Add a Widget Component to this actor.
3. Configure the Widget Component with the following key settings:
    - **Widget Class**: Specify the UMG UI to use.
    - **Draw Size**: Set the "resolution" of the draw surface.
    - **Rendering Options**: Adjust background color, blend mode, two-sided rendering, and opacity.
4. Scale the entire actor to adjust its size in the world, independent of the Draw Size.

It's important to note that scaling the actor and adjusting the Draw Size work together to determine the final appearance of your UI in the VR space.

5.5.6 Connecting UI Events to the Game World

While UMG UI provides a powerful system for creating interfaces, it's important to understand that these UI elements cannot directly interact with the game world. This is because the UMG UI is not an actor in itself within the level.

To enable interaction between your UI and the game world, there are two primary methods:

1. Connect UMG events to events in the menu actor
2. Set variables on the UMG UI to allow it to act in the world

In both cases, you need to cast to your UI class to access the necessary functions or variables. This involves getting the widget, calling `GetUserWidgetObject`, and then casting to your specific UI class. Note that this process does not work in the Construction Script; you should perform it in the `BeginPlay` event instead to ensure the widget is created before you attempt to access it.

5.5.6.1 Connecting to Events in the Menu Actor

To connect events from your UMG UI to events in your menu actor:

1. Cast to your widget class.
2. Get the button (or similar UI element) you want to interact with.
3. Bind the button's event to a custom event in your menu actor.

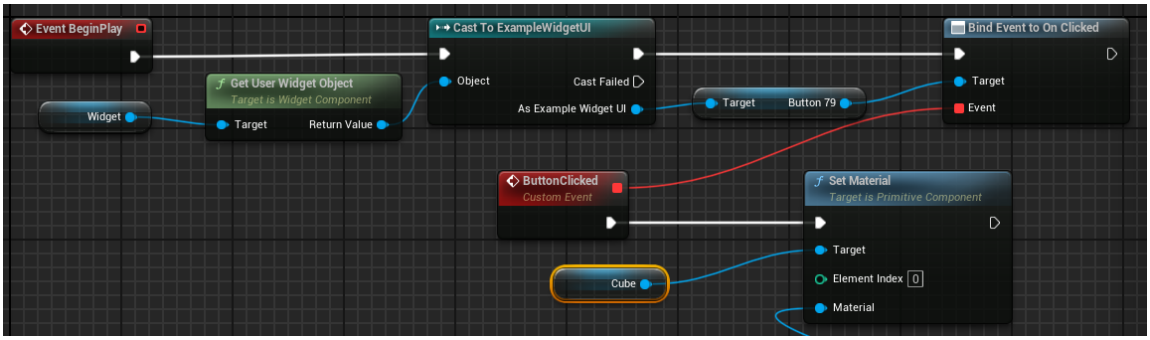


Figure 5.9: Binding UMG Event

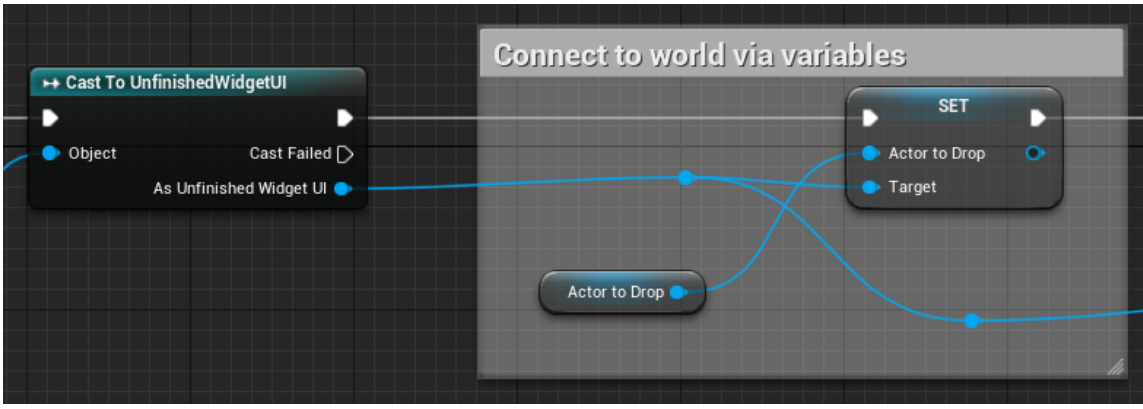
This approach allows you to handle UI events, such as button clicks, directly within your menu actor, facilitating interaction with the game world.

5.5.6.2 Setting Variables and Using Events in UMG

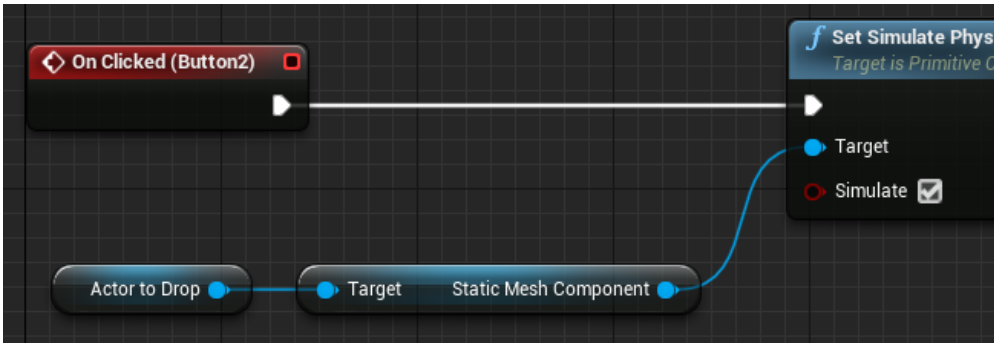
Alternatively, you can set variables on your UMG UI to enable it to act in the world:

1. Make the necessary variables in your UMG UI public.
2. Cast to your widget class and set these variables from your menu actor.
3. Handle events within your UMG UI, using the variables you've set to affect the game world.

In the Menu Actor:



In the UMG Widget Blueprint:



By setting variables on your UMG UI, you allow the UI to perform actions in the game world based on user interactions, enhancing the interactivity of your application.

5.6 Principles of 3D UI Design

When designing UI for 3D spaces, consider the following principles:

1. **Spatial Awareness**: UI elements should be placed in logical locations within the 3D space. For example, a menu might appear on a virtual wall or float in front of the user at a comfortable distance.
2. **Depth and Layering**: Utilize depth to create hierarchy and organization in your UI. Important elements can be brought closer to the user, while less critical information can be pushed further back.
3. **Interaction Paradigms**: Design UI elements that can be interacted with using natural gestures. For example, buttons that can be pressed with virtual hands or laser pointers.
4. **Scale and Readability**: Ensure that text and UI elements are large enough to be read comfortably in VR. Consider the resolution limitations of current VR headsets.
5. **Field of View**: Remember that VR headsets have a limited field of view. Avoid placing crucial UI elements at the extreme edges of the user's vision.
6. **Context-Sensitive UI**: Consider implementing UI elements that appear or become more prominent based on the user's context or actions within the virtual environment.

5.6.1 Importance of Collision in 3D UI

Collision detection plays a crucial role in creating interactive 3D UIs. It allows users to interact with UI elements as if they were physical objects in the virtual space.

Key points about collision in 3D UIs:

1. **Enable collision for UI elements**: This allows them to be "touched" by the user's virtual hands or pointers.
2. **Use overlap events**: These can trigger actions when the user's hand or pointer enters the UI element's collision volume.
3. **Consider different collision shapes**: Some UI elements might benefit from more complex collision shapes than simple boxes or spheres.

For more detailed information on implementing collision in Unreal Engine, refer to the next chapter which covers this topic in depth.

5.6.2 Triggering Actions Upon Touch

3D buttons in VR can be implemented using collision and overlap events. Here's a basic approach:

1. Create a 3D mesh for your button (e.g., a simple cube).
2. Enable collision on the button mesh.
3. Implement an overlap event that triggers when the user's hand or pointer enters the button's collision volume.
4. In the overlap event, trigger the desired action (e.g., change a scene, open a menu, etc.).

This approach allows for intuitive, physical-feeling interactions with UI elements in 3D space.

5.6.3 Advanced UI Concepts

5.6.3.1 Diegetic UI

Diegetic UI elements are those that exist within the game world itself. For example, a health meter on the player's in-game wrist device, or ammunition count displayed on the weapon itself. These UI elements can greatly enhance immersion by blending seamlessly with the virtual environment.

5.6.3.2 Spatial UI

Spatial UI takes advantage of the 3D environment to present information in a way that's impossible in 2D interfaces. For example, a 3D scatter plot that the user can walk through and examine from different angles.

5.6.3.3 Adaptive UI

Consider implementing UI that adapts to the user's position and orientation in the virtual space. This could involve UI elements that follow the user at a comfortable distance, or rearrange themselves based on the user's viewing angle.

5.6.4 Conclusion

Designing effective user interfaces for 3D spaces in XR requires a shift in thinking from traditional 2D UI design. By leveraging the unique capabilities of VR and AR, designers can create intuitive, immersive interfaces that enhance the overall user experience. As XR technologies continue to evolve, we can expect to see even more innovative approaches to UI design in 3D spaces.

For more information on UI design in Unreal Engine, refer to the Unreal Engine UMG UI Designer Documentation.

5.7 Haptics and Tactile Feedback

Haptic feedback plays a crucial role in creating immersive experiences in Extended Reality (XR). By providing tactile sensations, haptics enhance the sense of presence and interaction in virtual environments. This section provides a comprehensive exploration of haptic technologies in XR, from simple vibrations to advanced tactile technologies.

Note: While Section 2.5 introduces haptic technologies as part of emerging XR innovations, this chapter serves as the definitive guide to understanding, implementing, and designing haptic feedback in XR applications.

5.7.1 The Importance of Touch in XR

Haptics, the sense of touch in virtual reality (VR), plays a crucial role in creating immersive experiences. The ability to physically interact with virtual objects significantly enhances the realism and engagement of VR applications. This concept builds upon the famous "rubber hand illusion," which demonstrates how our brains can be tricked into perceiving an artificial limb as part of our body.

5.7.2 Types of Haptic Feedback

5.7.2.1 1. Controller Vibration

The most common form of haptic feedback in current VR systems is controller vibration. This provides a basic level of tactile feedback for interactions such as:

- Touching or colliding with virtual objects
- Firing a virtual weapon
- Receiving in-game notifications

While simple, controller vibration can significantly enhance the sense of interaction in VR when used effectively.

5.7.2.2 2. Advanced Haptic Controllers

More sophisticated haptic controllers are being developed to provide more nuanced and realistic tactile sensations. For example:

YouTube Video

Advanced Haptic Gloves Demo
See sophisticated haptic feedback technology in action, demonstrating variable resistance, texture simulation, and pressure sensations. These advanced haptic gloves provide realistic touch feedback when grasping and manipulating virtual objects in immersive environments.
Watch at: https://www.youtube.com/watch?v=4ODO4AcCIQY&t=s

These advanced controllers can provide:

- Variable resistance when grasping objects
- Texture simulation
- Pressure sensations

Some of these advanced haptic devices are probably available, but they're not targeted at consumers. They tend to be really expensive and focus on enterprise applications.

5.7.2.3 3. Passive Haptics

Passive haptics refers to the use of physical objects that correspond to virtual elements in a VR environment. This technique allows users to touch and feel virtual objects, greatly enhancing the sense of presence and immersion.

One notable example came from a company called The Void (which unfortunately closed in 2021). They created experiences where you walk around with VR equipment in spaces with physical constructions built to match the virtual environment. You could reach out to touch virtual objects and actually feel their physical counterparts.

Figure 5.10: Passive haptics example in The Void.

This approach allows users to physically interact with their surroundings while experiencing a virtual overlay, creating a powerful blend of digital and physical realities.

5.7.3 Passive Haptics in Mixed Reality (MR)

In Mixed Reality applications, passive haptics can be particularly effective. By matching virtual objects to real-world counterparts, developers can create convincing tactile experiences. For example:

- A virtual table that corresponds to a physical table in the user's environment
- Virtual walls that align with the real walls of a room

This approach not only enhances the sense of immersion but also contributes to user safety and confidence in movement within the virtual space. As users can physically feel the boundaries of their environment, they can move more freely and naturally within the virtual world.

5.7.4 Haptic Gloves

Haptic gloves represent a significant advancement in tactile feedback for VR interactions. These gloves incorporate motors and mechanisms that provide resistance and sensations to the user's fingers, allowing them to:

- Feel the sensation of grasping virtual objects
- Experience resistance when squeezing or pulling items
- Receive varied haptic feedback based on different virtual textures and materials

While currently aimed at enterprise applications due to their cost, haptic gloves represent a promising direction for enhancing the tactile dimension of VR experiences.

5.7.5 Implementing Haptic Feedback in Unreal Engine

While Unreal Engine doesn't directly support advanced haptic devices, it does provide ways to implement basic haptic feedback through controller vibration. Here's a simple approach:

1. **Detect Collision**: Use collision events to detect when a user interacts with a virtual object.
2. **Trigger Haptic Feedback**: Use the "Play Haptic Effect" node in Blueprints to trigger a vibration on the controller.
3. **Customize Feedback**: Adjust the intensity and duration of the vibration based on the type of interaction.

For more advanced haptic implementations, you may need to use plugins or custom C++ code to interface with specific haptic devices.

5.7.6 Best Practices for Haptic Design

When designing haptic feedback for XR experiences, consider the following:

1. **Subtlety**: Haptic feedback should enhance the experience, not overwhelm it. Use varying intensities based on the importance of the interaction.
2. **Consistency**: Establish a consistent haptic language across your application. Similar interactions should have similar haptic feedback.
3. **Latency**: Minimize the delay between visual events and haptic feedback to maintain the illusion of physical interaction.
4. **Context**: Consider the context of the interaction. A soft object should provide different feedback compared to a hard object.
5. **User Comfort**: Provide options for users to adjust or disable haptic feedback, as some may find strong vibrations uncomfortable.

5.7.7 Future of Haptics in XR

The field of haptics in XR is rapidly evolving. Some promising areas of development include:

- **Ultrasonic Haptics**: Creating tactile sensations in mid-air using focused ultrasound waves.
- **Thermal Feedback**: Simulating temperature changes to enhance realism in virtual environments.
- **Force Feedback**: Advanced systems that can simulate the weight and resistance of virtual objects.

As these technologies mature and become more accessible, we can expect XR experiences to become increasingly tactile and immersive.

5.7.8 Conclusion

Haptics and tactile feedback are crucial elements in creating truly immersive XR experiences. From simple controller vibrations to advanced haptic gloves and passive haptics, these technologies bridge the gap between the virtual and physical worlds. As XR continues to evolve, we can expect haptic feedback to play an increasingly important role in creating convincing and engaging virtual environments.

For more information on implementing basic haptic feedback in Unreal Engine, refer to the Unreal Engine Force Feedback Documentation.

5.8 Gesture and Voice Recognition in XR

Gesture and voice recognition technologies are becoming increasingly important in XR (Extended Reality) applications, offering more natural and intuitive ways for users to interact with virtual environments. These input methods can complement or even replace traditional controller-based interactions, enhancing immersion and accessibility in XR experiences.

Note: This chapter provides comprehensive coverage of gesture and voice recognition fundamentals, implementation techniques, and design best practices for XR applications. For AI-enhanced gesture and voice recognition technologies, see Section 8.6.2.

5.8.1 Gesture Recognition in XR

Gesture recognition allows users to interact with virtual objects and interfaces using natural hand movements and poses. This technology has seen significant advancements in recent years, particularly in the context of XR applications.

5.8.1.1 Types of Gesture Recognition

1. **Controller-based Gestures**: These rely on the motion and orientation of handheld controllers to interpret gestures.
2. **Camera-based Hand Tracking**: Uses external or headset-mounted cameras to track hand and finger movements without the need for controllers.
3. **Glove-based Systems**: Specialized gloves with sensors that provide precise finger tracking and sometimes haptic feedback.

5.8.1.2 Common Gestures in XR

Some commonly implemented gestures in XR applications include:

- Pinch to grab or select
- Swipe to scroll or navigate menus
- Open hand to release objects
- Point for UI interaction
- Thumbs up/down for quick feedback

5.8.1.3 Implementing Gesture Recognition

In Unreal Engine, gesture recognition can be implemented through:

1. **Motion Controller Components**: For controller-based gestures
2. **Vision-based Plugins**: For camera-based hand tracking (e.g., Oculus Hand Tracking plugin)
3. **Custom Gesture Recognition Systems**: Using Blueprint or C++ to define and recognize specific hand poses and movements

5.8.2 Voice Recognition in XR

Voice commands offer a hands-free way to interact with XR environments, which can be particularly useful when the user's hands are occupied or when accessibility is a concern.

5.8.2.1 Applications of Voice Recognition in XR

1. **Navigation**: Using voice commands to move through virtual spaces or menus
2. **Object Manipulation**: Selecting, moving, or modifying virtual objects
3. **System Control**: Adjusting settings or launching applications
4. **Text Input**: Dictating text for messaging or search functions
5. **AI Assistants**: Interacting with virtual AI assistants within the XR environment

5.8.2.2 Implementing Voice Recognition

While Unreal Engine doesn't have built-in voice recognition capabilities, developers can integrate third-party solutions:

1. **Platform-specific SDKs**: Using voice recognition APIs provided by VR/AR platforms (e.g., Oculus Voice SDK)
2. **Cloud-based Services**: Integrating services like Google Cloud Speech-to-Text or Amazon Transcribe
3. **Middleware Solutions**: Using plugins that provide voice recognition functionality

5.8.3 Challenges in Gesture and Voice Recognition

1. **Accuracy**: Ensuring reliable recognition across different users and environments
2. **Latency**: Minimizing delay between user input and system response
3. **User Training**: Familiarizing users with available gestures and voice commands
4. **Privacy Concerns**: Addressing user concerns about voice data collection and processing
5. **Multilingual Support**: Providing recognition for multiple languages and accents

5.8.4 Best Practices for XR Gesture and Voice Interactions

1. **Intuitive Design**: Design gestures and voice commands that feel natural and are easy to remember
2. **Visual Feedback**: Provide clear visual cues to confirm recognized gestures and voice commands
3. **Multimodal Input**: Combine gesture and voice input with traditional controls for flexibility
4. **Customization**: Allow users to customize gesture and voice commands to their preferences
5. **Fallback Options**: Provide alternative input methods for all gesture and voice-controlled functions

5.8.5 Future Trends

The field of gesture and voice recognition in XR is rapidly evolving. Some emerging trends include:

1. **Improved AI and Machine Learning**: Enhancing recognition accuracy and adapting to individual users
2. **Haptic Feedback**: Combining gesture recognition with haptic feedback for more immersive interactions
3. **Brain-Computer Interfaces**: Exploring direct neural interfaces for even more intuitive control
4. **Emotional Recognition**: Interpreting user emotions through voice tone and facial expressions
5. **Context-Aware Systems**: Adapting gesture and voice interactions based on the user's current activity or environment

5.8.6 Conclusion

Gesture and voice recognition technologies offer exciting possibilities for creating more natural, intuitive, and immersive XR experiences. As these technologies continue to advance, we can expect to see increasingly sophisticated and seamless interactions between users and virtual environments. Developers should consider incorporating these input methods to enhance the usability and accessibility of their XR applications, while being mindful of the challenges and best practices associated with their implementation.

For more information on implementing motion controls in Unreal Engine, which can be a starting point for gesture recognition, refer to the Unreal Engine Motion Controller Documentation.

5.9 Advanced Avatar Technologies and Digital Humans

The rapid advancement of avatar technologies is revolutionizing how we represent ourselves in virtual and augmented reality spaces. From Meta's high-end codec avatars to freely available tools like Epic Games' Metahuman, the push for photorealistic digital representations is gaining momentum.

This section focuses on the technical implementation and practical tools for creating advanced avatars. For the foundational psychological principles underlying virtual embodiment—including the Rubber Hand Illusion, body ownership, and the Proteus Effect—see Section 1.4.

5.9.1 Meta Codec Avatars: Pushing the Boundaries of Realism

Meta (formerly Facebook) has demonstrated some of the most advanced avatar technology to date with their codec avatars.These highly realistic digital representations showcase the potential for lifelike interactions in virtual environments.

YouTube Video

Meta Codec Avatars Technology Demo
Witness photorealistic digital human representations with real-time facial animation, showcasing the cutting-edge scanning and rendering technology that creates lifelike avatars for immersive social interactions in virtual reality environments.
Watch at: https://www.youtube.com/watch?v=MVYrJJNdrEg&t=s

Key features of Meta Codec Avatars:

1. Photorealistic rendering: The avatars achieve a level of detail that closely mimics real human faces.
2. Real-time animation: Facial expressions and movements are captured and rendered in real-time.
3. Custom scanning process: Currently, users need to visit a Meta lab for precise facial scanning.

This clip shows an interview between Mark Zuckerberg and Lex Fridman where both faces you see are actually computer-generated graphics. These avatars are created in real-time based on recorded data and tracking capabilities of advanced headsets that understand how the eyes, mouth, and other facial features move.

While incredibly impressive, it's important to note that this technology is not yet generally available to the public. The requirement for specialized scanning equipment limits its current accessibility.

5.9.2 Epic Games' Metahuman: Democratizing Realistic Avatar Creation

Epic Games, known for their Unreal Engine technology, has released Metahuman Creator, a tool that aims to make highly realistic avatar creation more accessible to developers and content creators.

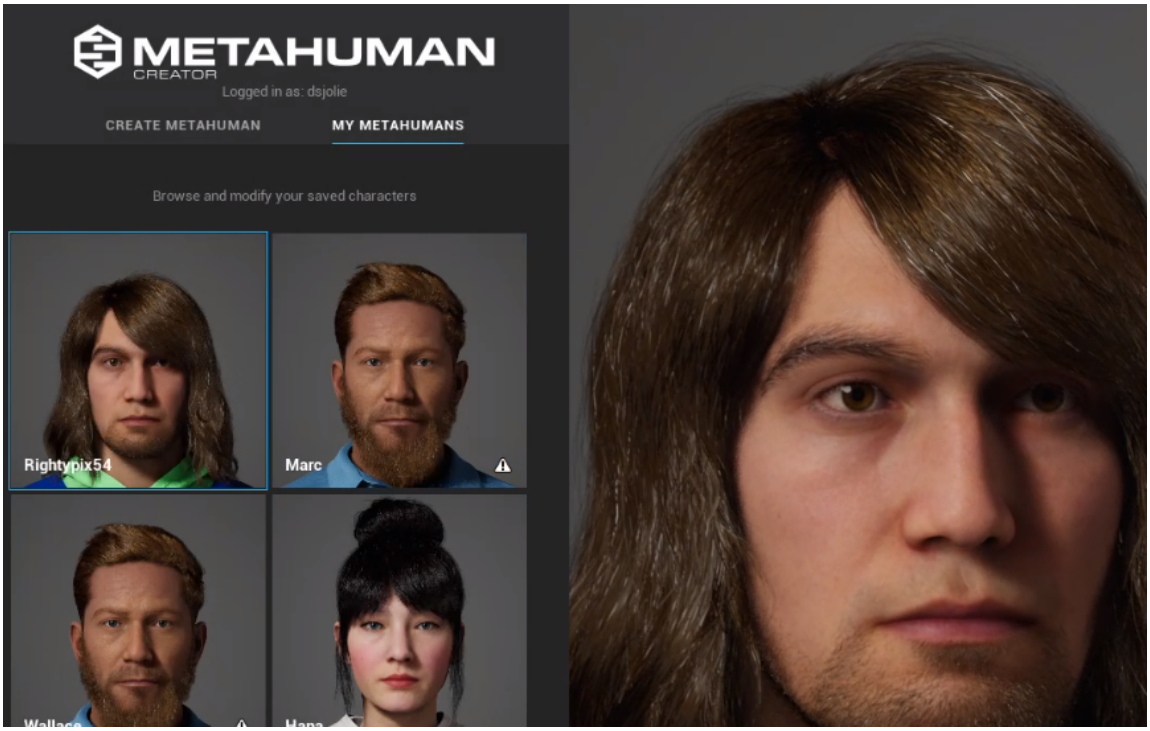


Figure 5.11: Various Metahuman avatars showcasing the diversity and realism achievable.

Metahuman Creator offers:

1. Browser-based creation: Users can craft detailed human avatars directly in their web browser.
2. Extensive customization: A wide range of facial features, hairstyles, and other attributes can be adjusted.
3. Integration with game engines: The created avatars can be easily imported into Unreal Engine for use in games or other interactive experiences.

Metahuman Creator is one of the tools that's freely available for creating realistic digital humans, and it represents how Epic Games is pushing this technology forward. You can explore it yourself at the link provided.

For those interested in exploring Metahuman Creator, you can access it at https://metahuman.unrealengine.com/.

5.9.3 Live Link Face: Bringing Avatars to Life

Building upon the Metahuman technology, Epic Games has also introduced Live Link Face, an iPhone app that enables real-time facial animation capture.

YouTube Video

Metahuman Live Link Face Animation
Discover how iPhone facial capture technology drives high-quality Metahuman avatars in real-time, demonstrating accessible tools for creating professional facial animations without expensive motion capture equipment for immersive character development.
Watch at: https://www.youtube.com/watch?v=V--tYfl8m38&t=s

This technology allows developers to:

1. Capture facial expressions in real-time using an iPhone's front-facing camera.
2. Apply the captured animations to Metahuman avatars instantly.
3. Create high-quality facial animations without the need for expensive motion capture equipment.

You can achieve this level of quality now with freely available tools and software, using just an iPhone or similar device.

This combination of Metahuman and Live Link Face represents a significant step towards making high-quality avatar creation and animation accessible to a broader range of creators and developers.

5.9.4 GaussianAvatars: The Future of Photorealistic Avatars

Recent research has explored the application of Gaussian Splatting techniques to avatar creation, resulting in the development of GaussianAvatars.

YouTube Video

GaussianAvatars Research Demo
Explore cutting-edge avatar technology using Gaussian Splatting techniques to create unprecedented photorealistic digital humans with efficient rendering performance and realistic deformation capabilities for next-generation immersive experiences.
Watch at: https://www.youtube.com/watch?v=lVEY78RwU_I&t=s

Key aspects of GaussianAvatars:

1. Photorealistic rendering: Achieves an unprecedented level of realism in digital human representation.
2. Efficient performance: Leverages Gaussian Splatting for improved rendering speed and quality.
3. Rigged 3D Gaussians: Allows for realistic deformation and animation of the avatar.

This is a very interesting development for creating photorealistic avatars that could become more readily available to developers and content creators.

While still in the research phase, GaussianAvatars represent a promising direction for the future of avatar technology, potentially offering even more realistic and efficient avatar representations for immersive environments.

5.9.5 Implementation Considerations and Cross-Platform Compatibility

As avatar technologies become more sophisticated, several practical considerations emerge for developers and content creators:

Technical Integration: - Cross-platform compatibility between different VR systems - Performance optimization for real-time rendering - Integration with existing game engines and development pipelines

Accessibility and Inclusivity: - Ensuring avatar creation tools are accessible to users with different technical skills - Providing diverse representation options in avatar creation systems - Accommodating users with disabilities in avatar design

Ethical Design Principles: The psychological effects of avatar embodiment (covered in detail in Section 1.4) raise important ethical considerations for developers:

1. **Informed Consent**: Users should understand how avatar characteristics might influence their behavior and self-perception
2. **Representation**: Avatar systems should offer inclusive options for diverse user populations
3. **Privacy**: Biometric data used for avatar creation and animation should be handled responsibly

For a comprehensive understanding of the psychological foundations underlying these design considerations, see the discussion of virtual embodiment principles in Section 1.4.

Future Technical Directions: - Integration with haptic feedback systems for enhanced embodiment - Real-time emotion recognition and expression mapping - AI-driven avatar behavior and personality simulation

5.10 Further Reading

Chapter 5 focused on designing interactions for 3D spaces in XR, covering topics such as input methods, locomotion techniques, 3D user interfaces, and haptic feedback. We explored how to create intuitive and comfortable ways for users to navigate and interact with virtual environments. To deepen your understanding of spatial interaction design, consider these resources:

5.10.1 Additional Resources

- Meta Design docs: https://developers.meta.com/horizon/design/
  - Design guidelines and best practices for VR interactions from Meta.

6 Applications of XR Technologies

6.1 2025 Spotlight Applications: Why XR Here?

Recent deployments highlight how XR solves domain-specific problems across regulation, industry, and social impact. Use these case tiles as conversation starters when scoping new projects or pitching stakeholders.

6.1.1 Varjo XR-4 + Teleport: EASA-Qualified Mixed-Reality Flight Simulation

Scenario: European Aviation Safety Agency approval of a mixed-reality simulator that pairs Varjo XR-4 headsets with certified cockpit hardware.(Varjo Technologies 2024a)

Why XR here?

- Regulatory compliance: Mixed reality meets stringent pilot-training standards, allowing airlines to log official hours with flexible content updates.
- Cost containment: Operators swap scenery and emergency scenarios digitally instead of rebuilding physical mockups.
- Sensory fidelity: XR-4's retinal-resolution passthrough preserves cockpit instrumentation readability while blending synthetic visuals for complex weather training.

6.1.2 Unreal, Twinmotion, and Cesium: Industrial Digital Twins for AEC

Scenario: AEC teams stitch together geospatial data, architectural models, and real-time collaboration inside Unreal Engine using Twinmotion and Cesium integrations.(Epic Games 2024a)

Why XR here?

- Geospatial context: XR visualizes proposed infrastructure alongside real terrain, making stakeholder reviews intuitive.
- Iterative coordination: Designers, engineers, and contractors co-locate in virtual spaces to detect clashes before construction.

- Decision transparency: Immersive walk-throughs translate technical documentation into experiences that non-experts can evaluate.

6.1.3 Therapeutic VR in Prisons: Creative Acts Rehabilitation Program

Scenario: California prisons deploy VR modules combined with art therapy to support people transitioning out of solitary confinement.(Kelley 2024)

Why XR here?

- Emotional rehearsal: VR safely simulates stressful situations (grocery stores, family gatherings) before release.
- Documented outcomes: Facilities reported dramatic reductions in infractions—evidence that immersive therapy can complement systemic reforms.
- Human-centered design: Facilitators tailor content to participant fears, showing XR's role in trauma-informed care.

6.2 Architectural and Urban Visualization

Virtual Reality (VR) and Augmented Reality (AR) technologies have revolutionized the field of architectural visualization and urban planning. These immersive technologies offer new ways to experience and interact with unbuilt environments, providing significant advantages in design, presentation, and decision-making processes.

6.2.1 Immersive Architectural Visualization

Architectural visualization has become a well-established practice in the design industry, leveraging powerful tools like Unreal Engine to create immersive 3D environments. These digital representations allow architects and clients to explore and evaluate building designs before construction begins, serving as an invaluable decision-making tool.

> An amazing film or an amazing image? You know, I still have to imagine myself in this space to understand the impact and we could just never do that until recently. I mean, it's really just a couple of years ago.
>
> - *Quote from industry professional*

Figure 6.1: Architectural Visualization Example

The power of VR in architectural visualization lies in its ability to create a sense of presence within the designed space. This immersive quality allows users to experience the spatial conditions in a way that traditional 2D renderings or physical models cannot achieve.

> And I feel that, you know, the technology has reached a point where we can simulate those spaces to a degree where I can actually trick my body into feeling the spatial condition virtually.
>
> - *Quote from industry professional*

YouTube Video

Architecture in Virtual Spaces
This video explores how architects are using VR to create immersive experiences that allow clients to feel the spatial conditions of unbuilt environments. The discussion covers the evolution from traditional 2D renderings to fully immersive 3D spaces, demonstrating how VR technology has reached a point where it can effectively simulate spatial conditions and trick the human body into feeling present in virtual architectural spaces.
Watch at: https://www.youtube.com/watch?v=XZr_xRh-vmo&t=504s

6.2.2 Urban Planning and City Visualization

VR technology has also found significant applications in urban planning and city visualization. These tools allow planners, stakeholders, and citizens to experience proposed urban developments in an immersive and intuitive way.

One example of this is the virtual city visualization project at Chalmers University:

YouTube Video

Chalmers Virtual City Visualization
Experience multi-scale urban planning visualization that allows users to interact with city models both holographically (bird's-eye table view) and immersively at street level. This video demonstrates how different perspectives provide unique insights for urban development and planning decisions, highlighting the value of immersive visualization for stakeholders and planners.
Watch at: https://www.youtube.com/watch?v=f4GPnivRtPo&t=s

This project demonstrates how different scales of visualization can provide varied insights:

1. **Holographic interaction**: Viewing the city model as if it were on a table, allowing for a bird's-eye perspective
2. **Immersive street-level view**: Providing context and relatability to the real environment

The holographic interaction allows you to use your whole body to engage with the city model from above, while the street-level view provides a completely different perspective. When you're down at street level, you can imagine yourself standing there, looking up and seeing the environment in its proper context for better understanding.

6.2.3 Benefits of XR in Architecture and Urban Planning

1. **Enhanced Spatial Understanding**: XR allows clients and stakeholders to truly understand the scale and feel of a space before it's built.
2. **Iterative Design**: Architects can make real-time changes and immediately see the impact in an immersive environment.
3. **Collaborative Decision Making**: Multiple stakeholders can simultaneously explore and discuss a design in a shared virtual space.
4. **Cost and Time Savings**: By identifying design issues early in the virtual environment, costly changes during construction can be avoided.

5. **Public Engagement**: Urban planners can use XR to better communicate proposed changes to the public, increasing understanding and engagement.

6.2.4 Case Study: John Wick 3 Set Design

The production of "John Wick 3" showcases how VR can be used to prototype and visualize complex sets before they're physically built.

Using Unreal Engine, the production team was able to: - Explore set designs in VR months before physical construction - Create and adjust lighting in a virtual environment - Provide a spatial understanding of abstract set concepts - Allow actors, directors, and cinematographers to visualize scenes in advance

A production designer on the film emphasized the tool's importance.

> It became this tool that allowed us to visualize what this set look like and also helped us to create the lighting and the design of this thing months and months before any decisions had to be made on the physical set. It was such an abstract set that having this kind of spatial relationship and visualizing it from that point of view had tons of value. I can't imagine them doing this set without VR.
>
> - *Quote from film production designer*

YouTube Video

John Wick 3 Virtual Production Pipeline
Behind-the-scenes look at how Unreal Engine enabled virtual set design and previsualization months before physical construction. The video shows how directors, actors, and cinematographers could explore and refine scenes in VR before filming began, streamlining the creative process and improving set design outcomes.
Watch at: https://www.youtube.com/watch?v=ngudPwaAfIE&t=s

6.2.5 Conclusion

XR technologies have become indispensable tools in architecture and urban planning. By providing immersive, interactive experiences of unbuilt environments, they enable better design decisions, more effective communication, and ultimately, the creation of spaces that better serve their intended purposes. As these technologies continue to evolve, we can expect their role in shaping our built environment to grow even further.

6.3 Data Visualization in XR

Extended Reality (XR) technologies offer powerful new ways to visualize and interact with complex data sets. By leveraging the immersive and spatial nature of XR, data visualization can become more intuitive, engaging, and insightful.

6.3.1 The Power of Immersive Data Visualization

Immersive data visualization in XR goes beyond traditional 2D charts or graphs by allowing users to physically move through and interact with data in a three-dimensional space. This approach can make complex data more accessible and memorable.

These examples demonstrate how VR, AR, and immersive technologies can make data and information more impactful, memorable, and relatable to us as embodied humans. The physical engagement transforms abstract data into tangible, experiential knowledge.

6.3.2 Examples of XR Data Visualization

6.3.2.1 1. HoloCube: Augmented Reality for 3D Data Visualization

The HoloCube represents an innovative application of augmented reality (AR) technology for data visualization. This device consists of a physical box with AR markers that, when viewed through a smartphone or other AR-capable device, displays a 3D object that can be manipulated by the user.

The HoloCube presents itself as a 3D object that you can turn and twist in your hands to understand different types of three-dimensional information. This tactile manipulation creates an intuitive interface for data exploration.

YouTube Video

HoloCube: Immersive Data Visualization
This video demonstrates HoloCube, a mixed reality application for immersive data visualization. It shows how users can interact with complex datasets in 3D space, providing a more intuitive and engaging way to explore and understand data through augmented reality.
Watch at: https://www.youtube.com/watch?v=G26n_vY_418&t=s

6.3.2.2 2. Embodied Data Visualization: The Nasdaq Example

Moving beyond handheld devices, the concept of embodied data visualization aims to make data more memorable and relatable by connecting it to physical experiences. One example is a visualization of the Nasdaq stock exchange's value over time, represented as a series of steps. When you represent data this way, you get the physical sensation of walking up stairs, creating a different type of memory for how these values rise and fall. You can feel when there's a steep incline or gradual slope, embedding the data pattern in your muscle memory.

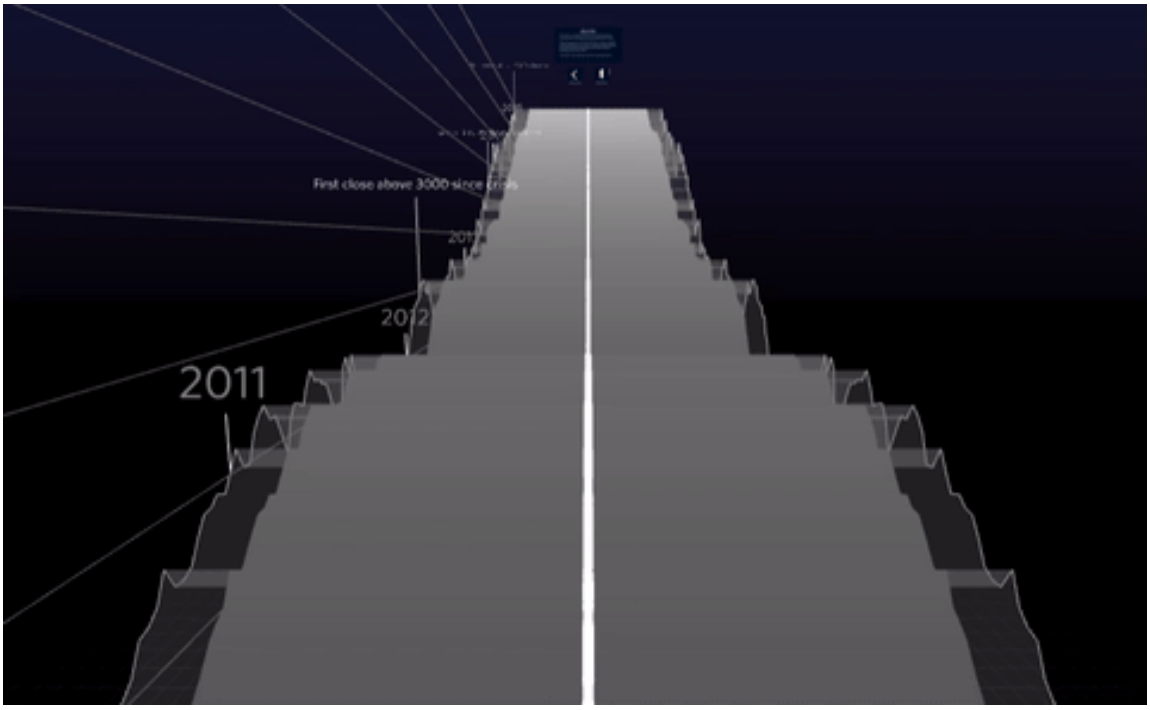


Figure 6.2: Visualization on Nasdaq value over time, as a stair to be climbed.

6.3.2.3 3. Data Sculptures: Physical and Virtual Representations

Data sculptures take embodied visualization a step further by creating large-scale, physical or virtual installations that users can interact with. These installations allow for a more immersive and physically engaging experience with data.

One example involves representing population data. Population data from different parts of the world is represented through physical models that you can walk into and examine

directly. You can step up to these representations and compare them to yourself and your own body scale, making abstract demographic statistics tangible and personally relatable.

This approach makes abstract population statistics tangible and comparable to human scale, potentially leading to more intuitive understanding of disparities and distributions.

Figure 6.3: WorldIndexer Installation, a physical example of spatial visualization. Watch the full video

6.3.3 Visualizing Death Tolls in Virtual Reality

A powerful example of using VR for data visualization is a project that represents death tolls from drone strikes.

Here the death toll is displayed as individual bodies arranged in a vast hall. As you walk through and navigate this space, you gain a visceral sense of the scope and what these numbers actually represent in human terms. The physical act of moving through the representation transforms statistics into emotional understanding.

This approach goes beyond traditional 2D charts or graphs by allowing the viewer to physically move through a space filled with representations of the deceased. Each body

in the virtual environment corresponds to a real person killed, creating a powerful and emotionally resonant experience.

YouTube Video

VR Death Toll Visualization
This video presents a powerful embodied data visualization where statistical casualties are represented as individual bodies in a virtual space. By allowing users to physically navigate through the representation, it creates emotional impact and a deeper understanding of the scale of loss.
Watch at: https://www.youtube.com/watch?v=Fc3lqak7tkE&t=s

6.3.4 Benefits of XR Data Visualization

1. **Spatial Understanding**: XR allows users to perceive data in three dimensions, potentially revealing patterns or relationships not apparent in 2D representations.
2. **Increased Engagement**: Immersive and interactive visualizations can make data exploration more engaging and memorable.
3. **Collaborative Analysis**: Multiple users can explore and discuss data together in a shared virtual space.
4. **Scale and Perspective**: XR enables users to view data at various scales, from overview to detail, simply by moving within the virtual space.
5. **Embodied Cognition**: By allowing users to physically interact with data, XR can leverage embodied cognition principles to enhance understanding.

6.3.5 Challenges and Considerations

While XR data visualization offers many benefits, there are also challenges to consider:

1. **Cognitive Overload**: Immersive 3D environments can potentially overwhelm users with too much information.
2. **Design Complexity**: Creating effective 3D visualizations requires new design skills and considerations.
3. **Accessibility**: Ensuring that XR data visualizations are accessible to users with various physical abilities.

4. **Technological Barriers**: The need for specialized hardware (VR/AR headsets) can limit widespread adoption.

6.3.6 Conclusion

XR technologies are opening up new frontiers in data visualization, offering ways to make complex data more intuitive, engaging, and impactful. As these technologies continue to evolve and become more accessible, we can expect to see increasingly sophisticated and insightful XR data visualizations across various fields, from business analytics to scientific research and beyond.

6.4 Education and Training Applications

Extended Reality (XR) technologies are revolutionizing education and training across various fields. By offering immersive, interactive experiences, XR can enhance learning outcomes, improve retention, and provide safe environments for practicing complex skills.

6.4.1 Why Immersive Learning Works: Theoretical Foundations

Before exploring specific applications, it's worth understanding why XR is particularly effective for learning. Several established learning theories help explain the educational power of immersive experiences.

Experiential Learning: Kolb's experiential learning cycle describes learning as a process of concrete experience, reflective observation, abstract conceptualization, and active experimentation. XR uniquely enables this entire cycle within a single session. A medical student can perform a virtual surgery (concrete experience), review their performance from different angles (reflective observation), understand the underlying anatomical principles through 3D visualization (abstract conceptualization), and immediately try again with modifications (active experimentation). The immersive nature compresses and intensifies this learning cycle in ways traditional instruction cannot match.

Situated Cognition: Learning occurs most effectively in authentic contexts that match how knowledge will be used. VR excels at providing contexts that would be expensive, dangerous, or impossible to access otherwise. A welding student learns not just the technique but also the physical context—the heat, the sparks, the spatial relationships. Language learners practice not in abstract grammar exercises but in simulated cultural contexts. This situatedness makes knowledge more transferable to real-world application because it was acquired in conditions that more closely approximate actual use.

Cognitive Load Theory: XR can both reduce and increase cognitive load, depending on design. Well-designed immersive experiences reduce extraneous cognitive load by making spatial relationships and three-dimensional structures immediately apparent rather than requiring mental rotation or visualization. A chemistry student seeing molecular structures in 3D space doesn't need to expend cognitive effort translating 2D diagrams. However, poor XR design can increase extraneous load through uncomfortable interfaces, motion sickness, or unnecessarily complex navigation. The key is designing experiences that leverage XR's ability to clarify spatial and procedural understanding while avoiding interface complexity that distracts from learning objectives.

Connection to Presence and Embodiment: These learning advantages connect directly to the presence and embodiment concepts discussed in **?@sec-presence** and Section 1.4. The sense of presence—the feeling of "being there"—is what enables the concrete experiences that drive experiential learning. Embodiment creates the authentic context that situated cognition requires. When students feel physically present in a virtual environment and embodied within it, they engage with content through the same perceptual and motor systems they'll use in real-world application. This alignment between learning context and application context is what makes immersive learning particularly effective.

These theoretical foundations explain why the following examples and applications demonstrate such strong learning outcomes. XR isn't just a novel delivery mechanism—it leverages fundamental principles of how humans learn most effectively.

6.4.2 Virtual Classrooms and Immersive Learning Environments

XR technologies can create virtual classrooms that go beyond traditional limitations.

When you have all students in a virtual environment, you can begin with something that essentially replicates a normal lecture situation. But once you establish that familiar foundation, you can then introduce 3D materials into the environment—essentially anything you can imagine. The possibilities become limitless.

Key advantages of virtual classrooms include: - Ability to visualize complex 3D concepts - Dynamic environment changes (e.g., transporting to historical locations) - Interactive demonstrations with virtual objects

Think of it like Hogwarts, essentially. You have a school where you want to teach using sound pedagogy, but you also have magic at your disposal. In VR, you can do anything—conjure any object, create any environment, and transport students anywhere. The educational possibilities are truly magical.

YouTube Video

VR Lecture Environment Concept
This video presents a concept for a virtual lecture environment, showing how XR can replicate and enhance traditional classroom experiences. It demonstrates the potential for immersive education, where students and teachers can interact with 3D content and each other in a shared virtual space.
Watch at: https://www.youtube.com/watch?v=PItLw_Mtec8&t=115s

6.4.3 Hands-on Training in Virtual Environments

XR technologies excel at providing hands-on training experiences, especially in fields where real-world practice might be dangerous, expensive, or impractical.

6.4.3.1 Example: Virtual Welding Lab

At University West, a project was undertaken to create a virtual welding lab:

- Collaboration with PTC (Production Technology Center)
- Utilization of photogrammetry to create 3D models of equipment
- Development of a virtual "exhibition" space
- Integration of instructional videos and information

This virtual lab serves multiple purposes: 1. Provides accessibility to expensive or potentially dangerous equipment 2. Offers a platform for remote learning and training 3. Creates an interactive space for showcasing technology and processes

6.4.4 Medical Training and Surgical Simulation

XR technologies have found significant applications in medical education and surgical training.

One particularly valuable application is in surgical training and review. Surgical operations can be recorded using volumetric video, allowing medical professionals to review procedures from multiple angles after the fact.

During live surgical procedures, there are often angles you can observe and others you wish you could see but cannot. With volumetric or free-viewpoint video recording, you can actually rotate the view and examine the procedure from different angles, seeing more of what's happening and better understanding how the surgery unfolds.

YouTube Video

Volumetric Video in Medical Training
This video demonstrates an advanced surgical training application using volumetric video capture to record and replay surgical procedures from any angle. Students can observe operations from perspectives impossible with traditional filming methods, enhancing medical education and surgical review.
Watch at: https://www.youtube.com/watch?v=d-hn2lSeOfk&t=s

This capability enhances the learning experience and can lead to improved surgical techniques and outcomes. For technical details on how volumetric video capture works, see Section 7.3.

6.4.5 Language Learning and Cultural Immersion

XR can provide immersive environments for language learning and cultural experiences. Students can be transported to virtual representations of foreign countries, practicing language skills in context and experiencing cultural nuances firsthand.

6.4.6 Benefits of XR in Education and Training

1. **Engagement**: Immersive experiences can increase student engagement and motivation.
2. **Experiential Learning**: XR allows for learning by doing, which can improve retention and understanding.
3. **Visualization of Abstract Concepts**: Complex or abstract ideas can be visualized in 3D, making them easier to grasp.
4. **Safe Practice Environment**: Students can practice dangerous or high-stakes procedures without real-world risks.
5. **Accessibility**: XR can make certain educational experiences more accessible to students regardless of physical location.

6.4.7 Challenges and Considerations

While XR offers many benefits for education and training, there are also challenges to consider:

1. **Cost**: High-quality XR equipment can be expensive, potentially limiting widespread adoption.

2. **Technical Expertise**: Educators need training to effectively use and create XR content.
3. **Content Development**: Creating high-quality educational XR experiences requires significant time and resources.
4. **Potential for Distraction**: Immersive environments might sometimes distract from learning objectives.
5. **Equity Issues**: Ensuring equal access to XR technologies for all students can be challenging.

6.4.8 Future Directions

As XR technologies continue to evolve, we can expect to see:

1. More sophisticated simulations for professional training
2. Increased use of AI to create adaptive learning experiences in XR
3. Greater integration of haptic feedback for more realistic training scenarios
4. Development of collaborative XR spaces for group learning and projects

6.4.9 Conclusion

XR technologies are transforming education and training by offering immersive, interactive, and engaging learning experiences. From virtual classrooms that can transport students anywhere in the universe to sophisticated simulations for professional training, XR is opening up new possibilities for how we learn and practice skills. As these technologies become more advanced and accessible, they have the potential to revolutionize education at all levels, making learning more effective, engaging, and accessible than ever before.

6.5 Healthcare and Therapy Uses

Extended Reality (XR) technologies are making significant impacts in the healthcare sector, offering innovative solutions for medical training, patient treatment, and therapeutic interventions. This section explores various applications of XR in healthcare and therapy.

6.5.1 Augmented Reality in Medical Procedures

Augmented Reality (AR) is finding applications in various medical procedures, providing real-time information and guidance to healthcare professionals.

6.5.1.1 Example: Vein Visualization

AR technology can be used to help medical professionals locate veins for injections or blood draws. By projecting a map of the patient's veins onto their skin, this technology can: - Improve accuracy of needle placement - Reduce patient discomfort - Increase efficiency of procedures

6.5.2 Mental Health and Therapy Applications

XR technologies offer new possibilities for mental health treatment and therapy.

6.5.2.1 Virtual Reality Exposure Therapy (VRET)

VRET is a form of exposure therapy that uses VR to create controlled environments for patients to confront their fears or anxieties. This can be particularly effective for treating: - Phobias (e.g., fear of heights, flying, or public speaking) - Post-Traumatic Stress Disorder (PTSD) - Anxiety disorders

The immersive nature of VR allows therapists to: - Create customized, gradual exposure scenarios - Control and adjust the intensity of the experience - Provide a safe, controlled environment for patients

6.5.2.2 Pain Management

VR has shown promise in pain management, particularly for chronic pain and during medical procedures. By immersing patients in engaging virtual environments, VR can: - Distract from pain sensations - Reduce anxiety associated with medical procedures - Potentially decrease the need for pain medication

6.5.3 Rehabilitation and Physical Therapy

XR technologies are being used to enhance rehabilitation and physical therapy programs.

6.5.3.1 Gamified Exercises

By turning rehabilitation exercises into immersive games, XR can: - Increase patient engagement and motivation - Provide real-time feedback on movement and progress - Allow for remote monitoring by healthcare professionals

6.5.3.2 Motor Skills Rehabilitation

For patients recovering from strokes or other neurological conditions, XR can provide: - Customized, adaptive exercises - Immersive environments that encourage movement - Visual feedback to help retrain motor skills

6.5.4 Challenges and Considerations

While XR offers significant benefits in healthcare, there are challenges to consider:

1. **Data Privacy and Security**: Ensuring patient data protection in XR applications.
2. **Integration with Existing Systems**: Seamlessly incorporating XR into current healthcare IT infrastructures.
3. **Regulatory Approval**: Navigating the process of getting XR medical applications approved by regulatory bodies.
4. **User Adoption**: Training healthcare professionals to effectively use XR technologies.
5. **Potential Side Effects**: Addressing issues like motion sickness or eye strain in some users.

6.5.5 Future Directions

As XR technologies continue to advance, we can expect to see:

1. More sophisticated surgical planning and visualization tools
2. Enhanced telemedicine capabilities using AR and VR
3. Integration of haptic feedback for more realistic medical simulations
4. Development of AI-powered virtual health assistants
5. Expanded use of XR in medical education and training

6.5.6 Conclusion

XR technologies are transforming healthcare by offering new tools for medical training, patient treatment, and therapeutic interventions. From enhancing surgical precision to providing innovative approaches to mental health treatment, XR is opening up new possibilities in healthcare. As these technologies continue to evolve and become more integrated into medical practice, they have the potential to significantly improve patient outcomes, enhance medical education, and revolutionize how healthcare is delivered.

6.6 Entertainment and Gaming

Extended Reality (XR) technologies have made a significant impact on the entertainment industry, particularly in gaming. This section explores how XR is reshaping entertainment experiences and revolutionizing game development.

6.6.1 VR Gaming: Immersive Experiences

Virtual Reality (VR) has transformed gaming experiences, offering two primary approaches:

6.6.1.1 1. Seated VR Gaming

Seated VR games create immersive cockpit-like environments, allowing players to control vehicles or spaceships without requiring physical movement.

A prime example is Elite Dangerous, a space simulation game.

This is an excellent example of VR's advantages in gaming, where you can design an entire cockpit environment with all controls positioned naturally around you. You can look left and right to access additional information that feels intuitively placed and easily accessible.

This setup provides several advantages: - Full 360-degree visual immersion - Intuitive control layouts - Reduced motion sickness issues - Simplified tracking and transportation problem-solving

YouTube Video

Elite Dangerous VR Space Combat
This video demonstrates seated VR gaming at its finest, showing how Elite Dangerous creates an immersive cockpit environment. Players can look around the detailed spacecraft interior, access controls positioned naturally around them, and experience space flight with full 360-degree visual immersion. This example illustrates how VR can enhance traditional gaming experiences without requiring room-scale movement.
Watch at: https://www.youtube.com/watch?v=Mlx-ooZv5qA&t=110s

6.6.1.2 2. Room-scale VR Gaming

Room-scale VR games utilize physical movement within a defined space, creating highly interactive experiences.

The game Unseen Diplomacy exemplifies this approach.

The game requires you to physically get down on your knees, use hand controls to unscrew screws, crawl through ducts, and follow complex twists and turns. This full-body engagement creates an unprecedented level of immersion and physical presence in the game world.

Key features of room-scale VR: - Full-body engagement - Complex environmental interactions - Clever level design to maximize limited physical space - Enhanced sense of presence

Developers use techniques like narrow turns to create the illusion of large environments within confined physical spaces.

YouTube Video

Unseen Diplomacy Room-Scale VR Gameplay
Experience room-scale VR gaming that requires crawling, crouching, and physical movement through air ducts and complex environments. This video showcases how clever level design maximizes limited physical space for immersive stealth gameplay, highlighting the unique possibilities of room-scale VR.
Watch at: https://www.youtube.com/watch?v=KirQtdsG5yE&t=s

6.6.2 XR in Film and Entertainment

XR technologies are not just transforming gaming; they're also reshaping how films are made and experienced.

6.6.2.1 Virtual Production in Filmmaking

VR and AR technologies are being used in film production, particularly for previsualization and virtual set design. The production of "John Wick 3" showcases this approach.

> It became this tool that allowed us to visualize what this set look like and also helped us to create the lighting and the design of this thing months and months before any decisions had to be made on the physical set. It was such

> an abstract set that having this kind of spatial relationship and visualizing it from that point of view had tons of value.
>
> - *Quote from production designer on John Wick 3*

Using Unreal Engine, the production team was able to: - Explore set designs in VR months before physical construction - Create and adjust lighting in a virtual environment - Allow actors, directors, and cinematographers to visualize scenes in advance

YouTube Video

John Wick 3 Virtual Production Behind-the-Scenes
This video provides a detailed look at the virtual production workflow using Unreal Engine for film set design. It demonstrates how VR previsualization streamlines film production by allowing creative teams to explore and iterate on set designs before physical construction, improving collaboration and creativity.
Watch at: https://www.youtube.com/watch?v=ngudPwaAfIE&t=s

6.6.2.2 360-degree Videos and Immersive Experiences

360-degree videos represent a significant advancement in immersive entertainment, offering viewers the ability to look around in any direction and feel present within filmed content.These videos have found particular success in entertainment applications where they can transport audiences to otherwise inaccessible locations.

Entertainment Applications: - **Nature documentaries**: Underwater scenes, wildlife encounters, and extreme environments - **Concert experiences**: Virtual front-row seats to live performances
- **Travel content**: Virtual tourism and location scouting - **Sports broadcasting**: Courtside or field-level viewing experiences

When you experience 360-degree video in a VR headset, you can simply turn your head to look around naturally. This represents one of the best applications for mobile VR headsets, where the interaction remains simple yet highly immersive.

User Experience Considerations: - **Immersive storytelling**: Directors must consider that viewers can look anywhere, changing traditional narrative control - **Comfort and accessibility**: Works particularly well for users who cannot physically travel or experience certain environments - **Social viewing**: Multiple users can share the same 360-degree experience while each controlling their own viewpoint - **Interactivity**: Only interactivity is to look around, if you try to move or interact in any other way your sense of presence may break.

YouTube Video

Immersive 360-Degree Underwater Experience
Dive into an underwater world through 360-degree video that showcases the power of immersive entertainment. This video allows viewers to look around freely and feel present in otherwise inaccessible ocean environments, demonstrating the potential of VR for nature documentaries and virtual tourism.
Watch at: https://www.youtube.com/watch?v=rG4jSz_2HDY&t=s

Note: For technical details on 360-degree video integration and implementation considerations, see Section 7.5.1 in Chapter 7.

6.6.3 AR in Entertainment

Augmented Reality (AR) is finding its place in entertainment through mobile applications and location-based experiences.

6.6.3.1 Mobile AR Games

Games like Pokémon Go have demonstrated the potential of AR in creating engaging, real-world interactive experiences. These games: - Blend virtual elements with the real world - Encourage physical activity and exploration - Create social experiences through shared AR environments

6.6.3.2 Location-Based AR Experiences

Theme parks and museums are incorporating AR to enhance visitor experiences: - Interactive exhibits that come to life through AR devices - Guided tours with AR overlays providing additional information - AR-enhanced rides that blend physical and virtual elements

6.6.4 The Future of XR in Entertainment

As XR technologies continue to evolve, we can expect to see:

1. More sophisticated and immersive VR gaming experiences
2. Increased use of XR in film production and virtual cinematography
3. Blending of physical and virtual elements in live performances and events
4. Development of shared virtual spaces for social entertainment experiences

5. Integration of haptic feedback and other sensory inputs for more immersive experiences

6.6.5 Challenges and Considerations

While XR offers exciting possibilities for entertainment, there are challenges to address:

1. **Motion Sickness**: Designing VR experiences that minimize discomfort for users
2. **Hardware Limitations**: Current XR devices may have limitations in resolution, field of view, or comfort for extended use
3. **Content Creation**: Developing high-quality XR content requires new skills and can be resource-intensive
4. **Accessibility**: Ensuring XR entertainment is accessible to users with various physical abilities
5. **Social Concerns**: Addressing potential issues of isolation or addiction in immersive virtual experiences

6.6.6 Conclusion

XR technologies are reshaping the landscape of entertainment and gaming, offering new ways to create and experience content. From fully immersive VR games to AR-enhanced real-world experiences, XR is opening up new frontiers in how we play, watch, and interact with entertainment. As these technologies continue to advance, we can expect to see even more innovative and engaging applications in the world of entertainment and gaming.

6.7 Immersive Cultural and Tourism Experiences

Virtual Reality (VR) technology is revolutionizing the way we experience tourism and cultural sites, offering immersive experiences that transport users to different parts of the world and even to imaginary realms. This section explores several innovative VR applications in tourism and cultural experiences.

6.7.1 Google Earth VR

Google Earth VR leverages Google's extensive 3D mapping data to provide virtual tours of cities around the world. This application allows users to:

- Explore 3D renderings of major cities

- Navigate freely through different parts of the world
- Experience changes in time of day within the virtual environment

The application allows you to navigate effortlessly from one part of the world to another, move around freely, and observe changes in time of day and other environmental conditions. This creates a fluid, global exploration experience.

While the application offers an impressive bird's-eye view of cities, it's worth noting that the detail at street level may be limited due to the nature of photogrammetry data used.

YouTube Video

Google Earth VR Global Exploration
Fly around the world in virtual reality using photogrammetry data to explore cities from impossible perspectives. This video demonstrates how VR transforms geographical exploration and virtual tourism through immersive bird's-eye views of real locations, making global travel accessible from home.
Watch at: https://www.youtube.com/watch?v=SCrkZOx5Q1M&t=s

6.7.2 Versailles VR

The Versailles VR project showcases the potential of high-detail photogrammetry in creating virtual tourism experiences. This ambitious project involved:

- Capturing the Palace of Versailles in extreme detail
- Using tens of thousands of photos to recreate the site
- Allowing users to navigate and explore the palace in virtual reality

I want to emphasize the project's scale.

The team undertook extremely ambitious photogrammetry work to capture Versailles in extraordinary detail, using tens of thousands of photographs—possibly more—to recreate much of what you would see during an actual visit to the palace. This level of detail creates an remarkably authentic virtual experience.

This level of detail allows for a highly immersive experience that closely mimics an actual visit to the palace.

YouTube Video

Versailles VR Virtual Palace Tour
Explore the Palace of Versailles through high-detail photogrammetry reconstruction. This video showcases how virtual tourism can provide access to historical sites with extraordinary detail and immersion that closely mimics physical visits, highlighting the potential of VR for cultural heritage.
Watch at: https://www.youtube.com/watch?v=ln-SceumPlI&t=s

6.7.3 Museum of Other Realities

The Museum of Other Realities (MOR) represents a different approach to virtual tourism and cultural experiences. Unlike recreations of physical places, MOR leverages the unique possibilities of VR to create:

- A virtual museum with various art installations
- Novel and interesting cultural experiences
- Artistic expressions that may not be possible in the physical world

This represents a different type of experience that isn't widely available yet, but I find it particularly fascinating in terms of the novel and interesting cultural experiences it can provide. It opens up entirely new possibilities for cultural engagement that transcend physical limitations.

This type of virtual experience opens up new possibilities for artistic expression and cultural exploration that go beyond the limitations of physical spaces.

YouTube Video

Museum of Other Realities Virtual Art Space
Experience a virtual museum that transcends physical limitations, featuring impossible art installations and cultural experiences. This video leverages VR's unique capabilities for artistic expression beyond what's possible in traditional gallery spaces, opening new frontiers for digital art.
Watch at: https://www.youtube.com/watch?v=zUtqvp1LIcM&t=s

6.7.4 The Void

The Void takes virtual reality experiences to another level by combining VR technology with physical environments and effects. This approach:

- Creates immersive experiences based on popular franchises like Star Wars and Ghostbusters
- Uses "magic theory and design" to enhance the sense of reality
- Allows users to step into and interact with fantasy worlds

> If we're going to put you inside a Star Wars, I mean, that's an impossible reality. That's not a reality that you're going to actually travel to and visit. So we use a lot of magic theory and design behind the scenes to help convince you, even if it's just subconsciously that these things are real.
>
> - *Quote from The Void*

The Void demonstrates how VR can be used to create fantastical tourism experiences, allowing people to visit and interact with imaginary worlds in ways that feel tangible and real.

YouTube Video

The Void Immersive VR Experience
Step into location-based VR that combines virtual worlds with physical environments and effects. This video shows how The Void creates fantastical tourism experiences in franchises like Star Wars, where users can tangibly interact with imaginary worlds through mixed physical and virtual elements.
Watch at: https://www.youtube.com/watch?v=fa52D-XYbkw&t=s

6.7.5 Implications for the Tourism Industry

The development of these immersive cultural and tourism experiences has significant implications for the tourism industry:

1. **Accessibility**: VR can make cultural sites and experiences accessible to those who may not be able to visit in person due to physical, financial, or geographical constraints.
2. **Preservation**: Detailed virtual recreations can aid in the preservation of historical sites and artifacts, allowing for their study and appreciation even if the physical locations become inaccessible.
3. **Pre-trip Planning**: Potential tourists can use VR to explore destinations before deciding to visit, potentially influencing their travel choices.
4. **Education**: These immersive experiences offer new ways to learn about history, culture, and art, supplementing traditional educational methods.

5. **New Forms of Entertainment**: Experiences like The Void blur the lines between tourism, entertainment, and storytelling, creating new opportunities for the tourism and entertainment industries.

As VR technology continues to advance, we can expect even more innovative and immersive applications in tourism and cultural experiences, further transforming how we explore and interact with the world around us.

6.8 Further Reading

Chapter 6 explored various real-world applications of XR technologies across different sectors, including education, healthcare, entertainment, and industry. We examined how VR, AR, and MR are being used to solve problems and create new opportunities in these fields. To gain a broader perspective on the current and future applications of XR, explore these resources:

6.8.1 Research Papers

- Riva, G., Baños, R. M., Botella, C., Mantovani, F., & Gaggioli, A. (2016). Transforming experience: the potential of augmented reality and virtual reality for enhancing personal and clinical change. Frontiers in psychiatry, 7, 164.
  - Explores applications of VR and AR in mental health and personal development.
- Somanath, S., et al. (2024). Towards Urban Digital Twins: A Workflow for Procedural Visualization Using Geospatial Data. Remote Sensing, 16(11), Article 11.
  - Demonstrates the application of XR technologies in urban planning and visualization.

6.8.2 Additional Resources

- IEEE VR Conference proceedings: https://ieeevr.org/
  - Annual conference proceedings showcasing the latest research and applications in virtual reality.
- Augmented World Expo (AWE) website: https://www.awexr.com/
  - Resources and news about the latest developments in AR and VR applications.

7 Reality capture

7.1 Photogrammetry and 3D Scanning

Photogrammetry is a powerful technique that allows the creation of detailed 3D models from a series of 2D photographs. This method has become increasingly accessible and powerful in recent years, thanks to advances in computing power and the widespread availability of high-quality cameras in smartphones.

7.1.1 Basic Principles of Photogrammetry

The core concept of photogrammetry involves:

1. Taking multiple photographs of an object or environment from different angles
2. Using software to track features across these images
3. Matching camera positions and orientations
4. Generating a 3D model based on the identified common points

As I often explain to my students, photogrammetry is essentially just taking a bunch of normal photos and letting the computer chew on them. I've found this process can work with "any" cameras, though the quality of the output will depend on the input image quality. Importantly, smartphone cameras are often sufficient for getting started with photogrammetry projects.

7.1.2 A Personal Example

In one project, I took my normal digital camera and captured about 100 photos of construction work we were doing behind our house in Trollhättan. Using default settings, I let the computer process the images for about an hour and a half, and it produced a detailed 3D environment.

This example illustrates how accessible the technology has become. With just a standard digital camera and some freely available software, it's possible to create a 3D model of a real-world environment in just a couple of hours.

View the 3D model

The resulting 3D model can be exported and used in various applications, such as virtual reality environments or game engines like Unreal Engine, allowing for virtual exploration and planning.

7.1.3 Aerial Photogrammetry

For larger scale projects, aerial photogrammetry using drones can be incredibly effective. While this requires more specialized equipment, it opens up possibilities for creating detailed 3D models of expansive areas.

Once you've made the initial investment—learning the software, acquiring a drone, and understanding the workflow—you can create detailed 3D models for VR/AR applications in real-world settings.

YouTube Video

Aerial Photogrammetry Process
Comprehensive overview of capturing large-scale environments from the air using systematic photography techniques to create detailed 3D models for urban planning, archaeology, and immersive virtual experiences of real-world locations.
Watch at: https://www.youtube.com/watch?v=wa_b9BRjXgk&t=s

This method allows for the creation of highly detailed 3D models of large environments, which can be invaluable for urban planning, archaeology, or creating immersive virtual experiences of real-world locations.

7.1.4 Large Scale Integration in Unreal Engine

Taking photogrammetry to the next level, it's possible to create incredibly detailed and expansive virtual environments by integrating photogrammetry data into game engines like Unreal Engine.

This example shows a monastery in a spectacular location. The creators captured thousands of photographs to build this virtual environment—essentially creating a digital copy of this real-world place.

YouTube Video

Large-Scale Photogrammetry in Unreal Engine
Stunning demonstration of a monastery location recreated through extensive photogrammetry and integrated into Unreal Engine, showcasing how massive real-world environments can become explorable virtual spaces with photorealistic detail.
Watch at: https://www.youtube.com/watch?v=BVvAY2gImjc&t=s

This example demonstrates how photogrammetry can be used to create highly detailed, explorable virtual environments based on real-world locations. It's worth noting that while most of the environment is captured through photogrammetry, some elements (like water bodies) might be added or enhanced using the game engine's capabilities.

7.1.5 Limitations and Challenges of Photogrammetry

While photogrammetry is a powerful tool, it comes with its own set of limitations and challenges:

1. **Time-Consuming Process**: It takes time for one just to gather these images.
2. **Reflections**: Reflective surfaces pose a significant challenge for photogrammetry software.

Reflections present a significant challenge because the software looks for recognizable features across images to understand spatial relationships. When you have reflections—imagine seeing a person in a mirror—the system can become confused about where the camera actually is in relation to these features.

3. **"Featureless" Surfaces**: Surfaces lacking distinct features or textures can be problematic. Surfaces lacking distinct features—like a plain white wall—pose problems because they don't provide enough structural information for the software to work with.
4. **Patterns**: While patterns can provide some texture, strictly repeating patterns can cause issues.

Patterns can be helpful, but strictly repeating patterns create difficulties. While patterns are better than featureless surfaces, repetitive patterns make it hard for the software to distinguish one section from another.

5. **Varying and Sharp Lighting**: Lighting conditions play a crucial role in the quality of photogrammetry results.

Varying lighting conditions, particularly outdoors with moving clouds or changing sun position, can significantly alter the appearance of objects across photos, creating additional processing challenges.

6. **Motion**: Photogrammetry requires a static subject.

Since photogrammetry relies on multiple photos taken over time, the subject must remain completely static throughout the capture process.

7.1.6 Conclusion

Photogrammetry has evolved from a specialized technique to an accessible tool for creating 3D models from photographs. Whether you're using a smartphone for small projects or professional equipment for large-scale environments, the principles remain the same. As technology continues to advance, we can expect even more impressive and accessible applications of photogrammetry in fields ranging from entertainment to scientific research.

7.2 3D Gaussian Splatting and Hybrid Workflows

3D Gaussian Splatting (3DGS) has matured from a research curiosity into a production-ready capture format that complements traditional photogrammetry. Instead of reconstructing polygon meshes, 3DGS stores scenes as millions of overlapping ellipsoids rendered directly by GPUs, enabling photorealistic, view-dependent effects with surprisingly small file sizes.

7.2.1 Artifact Taxonomy

- **Urban walkthroughs**: The Ludlow "Quality Square" capture demonstrates street-scale scans with navigable splat viewers and scanning-path visualizations.(Barrett 2024)
- **Macro specimens**: Honeybee macro captures use focus stacking across 1,700+ photos to showcase microscopic detail—perfect for museums and scientific storytelling.(Clarke 2024)
- **Hybrid architectural sets**: Hybrid real-estate demos combine synthetic interiors (generated from architectural renders) with photogrammetric backdrops for previsualization.(Eastcott 2024)
- **Industrial inspection**: Factory-floor "4D video scrubbers" compare splat captures over time to reveal maintenance issues.(Radiance Fields 2024)

> **!** Compression and fidelity
>
> Ludlow's professional workflow compresses a 1.2 GB raw scan down to a 50 MB web-ready splat without noticeable quality loss.(Barrett 2024) Expect to budget roughly 20–60 MB for room-scale captures and 150+ MB for dense outdoor scenes, making 3DGS viable for browser delivery and headset streaming.

7.2.2 Capture Accessibility in 2025

- **Quest-native capture**: Meta's Horizon Hyperscape records outdoor environments directly from Quest 3 headsets, uploading frames to the cloud for automated processing. This removes the dedicated camera requirement for student projects.(MuchRockness 2024)
- **Enterprise platforms**: Varjo's Teleport service ingests photos or prebuilt splats, stitches multiple rooms into portal-connected tours, and streams content to browsers or high-end headsets.(Varjo Technologies 2024b)
- **Consumer experiments**: Mobile apps such as Polycam and Luma export splats alongside meshes, letting you pick the representation that best fits your pipeline.

7.2.3 Preparing Splats for Engines

While many teams view 3DGS scenes in native viewers, you can now import splats into Unreal Engine or Unity via plugins (gsplat, InstantNGP integrations). When planning a project, sketch an "import checklist" alongside your photogrammetry workflow:

1. Export splats plus metadata (camera positions, scale) from your capture tool.
2. Convert to engine-friendly formats (PLY, Gaussian binaries) using open-source converters.
3. Set up level-of-detail switches or fallback meshes for devices without splat renderers.

See the content creation pipelines in Chapter 3 for practical examples of moving captured spaces into interactive experiences.

7.3 Volumetric Video Capture

Volumetric video is an advanced reality capture technique that offers unprecedented flexibility in viewing and interacting with recorded content. This technology goes beyond traditional video by capturing three-dimensional representations of subjects or scenes, allowing for free-viewpoint experiences.

7.3.1 Understanding Volumetric Video

Volumetric video capture involves recording a three-dimensional space, including depth information for each pixel. This results in a dynamic 3D model that can be viewed from any angle.

This technique uses three different Kinect camera views, each containing depth information for every pixel. This means the system knows not just the color of each pixel, but also its distance from the camera.

This depth information is crucial for reconstructing the scene in three dimensions, enabling viewers to move around and view the content from any desired angle.

YouTube Video

Free Viewpoint Video Demo
Demo of free viewpoint video: move around scenes using depth info and multi-camera capture for perspectives not possible with traditional video.
Watch at: https://www.youtube.com/watch?v=ptmHag3XwXY&t=s

7.3.2 Large-scale Volumetric Capture

For professional applications, large-scale volumetric capture setups are used. These typically involve:

1. A large space surrounded by green screens
2. Numerous cameras positioned strategically around the space
3. Performers acting within the capture area

YouTube Video

Large-Scale Volumetric Studio
Behind the scenes: hundreds of cameras and green screens for full 3D capture in immersive applications.
Watch at: https://www.youtube.com/watch?v=G0XUgnPl9KQ&t=s

This demonstrates large-scale volumetric capture with extensive green screen setups and numerous cameras—those dots visible on the walls are actually individual cameras.

7.3.3 Relightable Volumetric Video

An advanced form of volumetric capture is relightable volumetric video. This technique not only captures the three-dimensional form of performers but also records detailed information about the materials and surfaces being filmed.

This system captures detailed information about the materials and surfaces of performers. It calculates not only 3D shape but also how different colored lights should reflect off skin, clothing, and other materials.

YouTube Video

Relightable Volumetric Capture
Advanced tech: captures 3D geometry and material properties for relighting performances in post-production with dynamic virtual lighting.
Watch at: https://www.youtube.com/watch?v=anBRroZWfzI&t=s

The key advantage of this technique is the ability to relight the captured performance in post-production, allowing for seamless integration into virtual environments with dynamic lighting conditions.

7.3.4 Applications of Volumetric Video

7.3.4.1 Entertainment Industry

In the entertainment industry, volumetric video allows for innovative approaches to filmmaking and content creation. Actors can be recorded volumetrically and placed in 3D

environments, offering new possibilities for editing and storytelling.

This example shows a simpler setup where the actors don't actually have a complete 3D representation—they're only recorded from one direction. This limits the viewing angles, but they're still positioned in 3D space and work effectively as long as you don't move too far from the intended viewing position.

YouTube Video

Depthkit Volumetric Filmmaking
Volumetric video with simplified setups and limited camera angles: create 3D content with modest equipment, understanding single-sided capture limits.
Watch at: https://www.youtube.com/watch?v=MXRk1njT_hE&t=s

7.3.4.2 Medical Applications

Volumetric video technology offers unique technical advantages for medical applications due to its ability to capture precise spatial relationships and multi-angle perspectives. The technology's capacity to record depth information alongside visual data makes it particularly valuable for medical documentation and analysis.

Key technical benefits for medical use include: - **Multi-perspective recording**: Eliminates blind spots common in traditional video - **Spatial accuracy**: Preserves precise anatomical relationships - **Post-capture navigation**: Allows reviewers to examine procedures from optimal viewing angles - **Data persistence**: Creates reviewable archives for quality assurance and training

The technical challenges specific to medical environments include lighting constraints in sterile environments, equipment integration with existing medical systems, and ensuring capture quality meets professional medical standards.

For detailed applications in medical training and education, see Section 6.4.4.

7.3.5 Holoportation

Holoportation is an exciting application of volumetric video technology that enables real-time 3D capture and transmission of people and objects. This technology, when combined with augmented reality devices like Microsoft's HoloLens, creates a sense of presence and shared space between remote participants.

This demonstrates how multiple cameras capture a person in one location and project her as a hologram in another room, allowing the researcher to see her directly through his HoloLens.

YouTube Video

Holoportation Demo
Microsoft's tech: volumetric capture in one location, 3D hologram projection in another, enabling immersive remote presence with HoloLens.
Watch at: https://www.youtube.com/watch?v=7d59O6cfaM0&t=s

7.3.6 Challenges and Limitations

Despite its potential, volumetric video technology faces several challenges:

1. **Complex Setup**: The capture process requires extensive equipment and carefully controlled environments.

As these examples demonstrate, volumetric capture requires incredibly complex setups with significant limitations. Even with hundreds of cameras, the capture volume typically spans only a few meters in diameter.

2. **Capture Limitations**: Even with numerous cameras, it's challenging to capture every angle without shadows or occlusions, especially with multiple performers.
3. **Data Management**: The capture process generates enormous amounts of data that must be processed, stored, and rendered.

The process requires collecting enormous amounts of data and intensive processing. Compressing and rendering this data in real-time presents significant technical challenges.

4. **Rendering Complexity**: The resulting 3D data is complex and requires significant computational resources to render in real-time.
5. **Cost**: The equipment and processing required make this technology expensive and not widely accessible.

7.3.7 Conclusion

Volumetric video capture represents a significant leap forward in how we record and interact with visual content. From entertainment to medical training, this technology opens up new possibilities for creating immersive and interactive experiences. As hardware capabilities improve and algorithms become more sophisticated, we can expect volumetric video to become more accessible and widely adopted across various industries and applications.

7.4 Light Fields and Neural Rendering

Light field capture represents the pinnacle of 360-degree imaging technology, offering an almost compromise-free solution for immersive visual experiences. This cutting-edge technique goes beyond traditional 360° photography by allowing viewers to interact with the captured environment in ways that closely mimic real-world perception.

> **Note**: This chapter provides comprehensive coverage of light field capture technology, neural rendering techniques, and implementation details. For display-focused aspects of light field technology, see Section 2.5.3.

7.4.1 What is a Light Field?

To understand light field capture, we must first grasp the concept of a light field itself.

> The light field is a vector function that describes the amount of light flowing in every direction through every point in space.
>
> - *Wikipedia*

In simpler terms, a light field encompasses all the light passing through a given area (imagine a window) from every possible direction. This comprehensive capture of light information is what enables the creation of truly interactive and dynamic visual experiences.

7.4.2 Key Characteristics of Light Fields:

1. Captures ALL light passing through a defined space
2. Records light from ALL directions
3. Essentially creates one 180° image per pixel

The implications of this are profound. Unlike a standard photograph or even a 360° image, a light field capture allows viewers to change their perspective within the scene, revealing new details and altering reflections as if they were physically present in the environment.

7.4.3 Light Field Capture Technology

Capturing a light field requires specialized equipment and techniques. One method involves using a robotic arm equipped with a camera featuring a fisheye or wide-angle lens. This setup systematically moves the camera to capture images from multiple positions, creating a comprehensive sphere of light field data.

YouTube Video

Robotic Light Field Capture
Automated light field photography: robotic arm with wide-angle lens captures scenes from many positions for immersive viewing datasets.
Watch at: https://www.youtube.com/watch?v=h6WDyc525C0&t=s

This process results in a dataset that allows viewers to:

- Move their perspective within the captured scene
- Observe changes in reflections and object positions based on their viewpoint
- Experience a level of immersion far beyond traditional photography or videography

7.4.4 Understanding Light Fields in Practice

To better grasp the concept of light fields, consider the following visualization:

YouTube Video

Light Field Theory Visualization
Explains light field concepts: how rays from objects pass through space, showing principles behind light field capture and storage needs.
Watch at: https://www.youtube.com/watch?v=BXdKVisWAco&t=s

In this example, we can see how light from a single point on an object (in this case, a goat) passes through multiple points on an imaginary window. Each of these light paths represents a different viewing angle, and a light field capture stores information for all of these paths.

For each point in the captured space, you must store light information from all possible directions—creating massive data requirements.

This comprehensive data capture is what allows for the dynamic, interactive nature of light field displays.

7.4.5 Light Field Video

Recent advancements have led to the development of light field video technology. As presented at SIGGRAPH 2020, this technology introduces an end-to-end system for capturing, reconstructing, compressing, and rendering high-quality, immersive light field video content.

> We present immersive light video with a layered mesh representation. Most digital videos are either flat and two dimensional or they provide some depth perception through binocular parallax showing different but predetermined points of view for each eye. In contrast, we have built an end to end system for capturing, reconstructing, compressing and rendering high quality, immersive light field video content.
>
> - *Quote from Light field video*

YouTube Video

Light Field Video Capture
End-to-end system for immersive light field video: camera array setup and processing pipeline for video where users can move and look around.
Watch at: https://www.youtube.com/watch?v=SvRgkXQZIQg&t=s

The capture rig for this technology consists of.

> Capture rig consists of 46 times synchronized action sports cameras mounted on a 92 centimeter diameter plastic hemisphere. It is inexpensive and relatively easy to fabricate.
>
> - *Quote from Light field video*

7.4.6 Neural Rendering

Neural rendering is an emerging field that combines traditional computer graphics with machine learning techniques to create more realistic and dynamic visual content. While not explicitly covered in this book, it's worth mentioning as it's closely related to advanced light field technology.

Neural rendering can:

1. Enhance the quality of captured light fields
2. Generate novel views from sparse input data
3. Create photorealistic renderings of 3D scenes

This technology has the potential to overcome some of the limitations of traditional light field capture, such as the need for dense camera arrays.

7.4.7 Implications and Applications

The potential applications for light field technology and neural rendering are vast and exciting:

1. **Virtual Reality (VR)**: Creating ultra-realistic, navigable environments for VR experiences.
2. **Augmented Reality (AR)**: Enhancing real-world scenes with perfectly integrated digital elements.
3. **Film and Entertainment**: Allowing viewers to explore scenes from different angles, adding a new dimension to storytelling.
4. **Scientific Visualization**: Providing researchers with tools to examine complex 3D data in unprecedented detail.
5. **Architecture and Design**: Enabling immersive walkthroughs of buildings and spaces before they're constructed.

7.4.8 Challenges and Future Developments

While light field capture and neural rendering represent significant leaps forward in immersive imaging technology, they're not without challenges:

- **Data Volume**: Capturing and storing light field data requires enormous amounts of storage and processing power.
- **Capture Complexity**: Current capture methods can be time-consuming and require specialized equipment.
- **Display Technology**: Developing displays capable of reproducing light fields accurately is an ongoing area of research.

As technology advances, we can expect these challenges to be addressed, leading to more accessible and widespread use of light field capture and neural rendering technologies.

7.4.9 Conclusion

Light field capture and neural rendering stand at the forefront of immersive imaging technology, promising to revolutionize how we capture, view, and interact with visual content. As research progresses and technology improves, we can look forward to increasingly realistic and interactive visual experiences that blur the line between the digital and physical worlds.

7.5 Integrating Captured Reality in XR Experiences

Integrating captured reality into Extended Reality (XR) experiences is a crucial aspect of creating immersive and realistic virtual environments. This process involves combining various reality capture techniques with XR technologies to create seamless blends of real and virtual elements.

7.5.1 360-Degree Video Integration

360-degree video represents a fundamental reality capture technique that captures real-world environments for immersive reproduction in XR applications. This section focuses on the technical implementation and integration aspects of 360-degree video capture systems.

7.5.1.1 Technical Implementation

360-degree video capture involves specialized camera systems and processing pipelines:

Camera Systems: - Multi-camera rigs with overlapping fields of view - Dedicated 360-degree cameras (e.g., Ricoh Theta, Insta360) - Synchronization requirements for multi-camera setups

Processing Pipeline: - Stitching algorithms to combine multiple camera feeds - Geometric correction and calibration - Resolution optimization and compression

In a VR headset, you can simply turn your head to look around in any direction. This represents one of the most effective applications for mobile VR headsets.

YouTube Video

360-Degree Video Example
Immersive 360-degree video: 3DOF viewing lets users look in all directions with VR headsets, showing accessible reality capture for VR.
Watch at: https://www.youtube.com/watch?v=pCve1w1GFOs&t=s

7.5.1.2 Reality Capture Characteristics

Technical specifications and limitations: - **Degrees of Freedom**: Three rotational DOF (3DOF) - pitch, yaw, roll - **Interactivity Constraints**: View-only interaction, no positional tracking - **Resolution Distribution**: Non-uniform pixel density across viewing angles - **Temporal Synchronization**: Frame-rate matching between capture and playback systems

7.5.1.3 Integration Challenges

Key technical challenges in 360-degree video integration: - **Parallax Issues**: Stitching artifacts from multi-camera setups - **Motion Sickness**: Vestibular-visual mismatch in mobile content - **Bandwidth Requirements**: High-resolution spherical video streaming - **Storage Optimization**: Efficient encoding for immersive content

For entertainment applications and user experience considerations of 360-degree videos, see Section 6.6.2.2.

7.5.2 Computer Vision for Reality Integration

Computer vision plays a crucial role in integrating captured reality into XR experiences. It enables systems to understand and interact with the visual world, allowing for more seamless blending of real and virtual elements.

7.5.2.1 Motion Tracking

Motion tracking is a fundamental computer vision technique used to follow objects or features across video frames. It can be implemented in two main ways:

1. **Video-based tracking**: This method relies solely on analyzing sequential video frames to detect and follow features.

2. **Combined with IMU**: Motion tracking can be enhanced by integrating data from an Inertial Measurement Unit (IMU). This fusion of visual and sensor data often provides more robust and accurate tracking results.

7.5.2.2 SLAM (Simultaneous Localization and Mapping)

SLAM is a real-time technique that allows a system to: - Map an unknown environment - Track its own position within that environment simultaneously

This technology is crucial for applications like autonomous robots and augmented reality systems that need to understand and navigate their surroundings in real-time.

SLAM was originally developed for robotics, helping robots simultaneously map their environment while tracking their own position within that space.

7.5.3 AR Cloud and Mirror Worlds

The concept of SLAM is evolving towards more ambitious applications:

1. **AR Cloud**: A persistent, shared AR experience across devices and users.
2. **Mirror World**: A digital twin of the physical world, continuously updated and accessible.

This technology enables the creation of digital mirror worlds—similar to the digital twin concept we discussed earlier. By continuously scanning different locations, you build digital versions of various environments. When you return to these places, the system recognizes your location much more quickly.

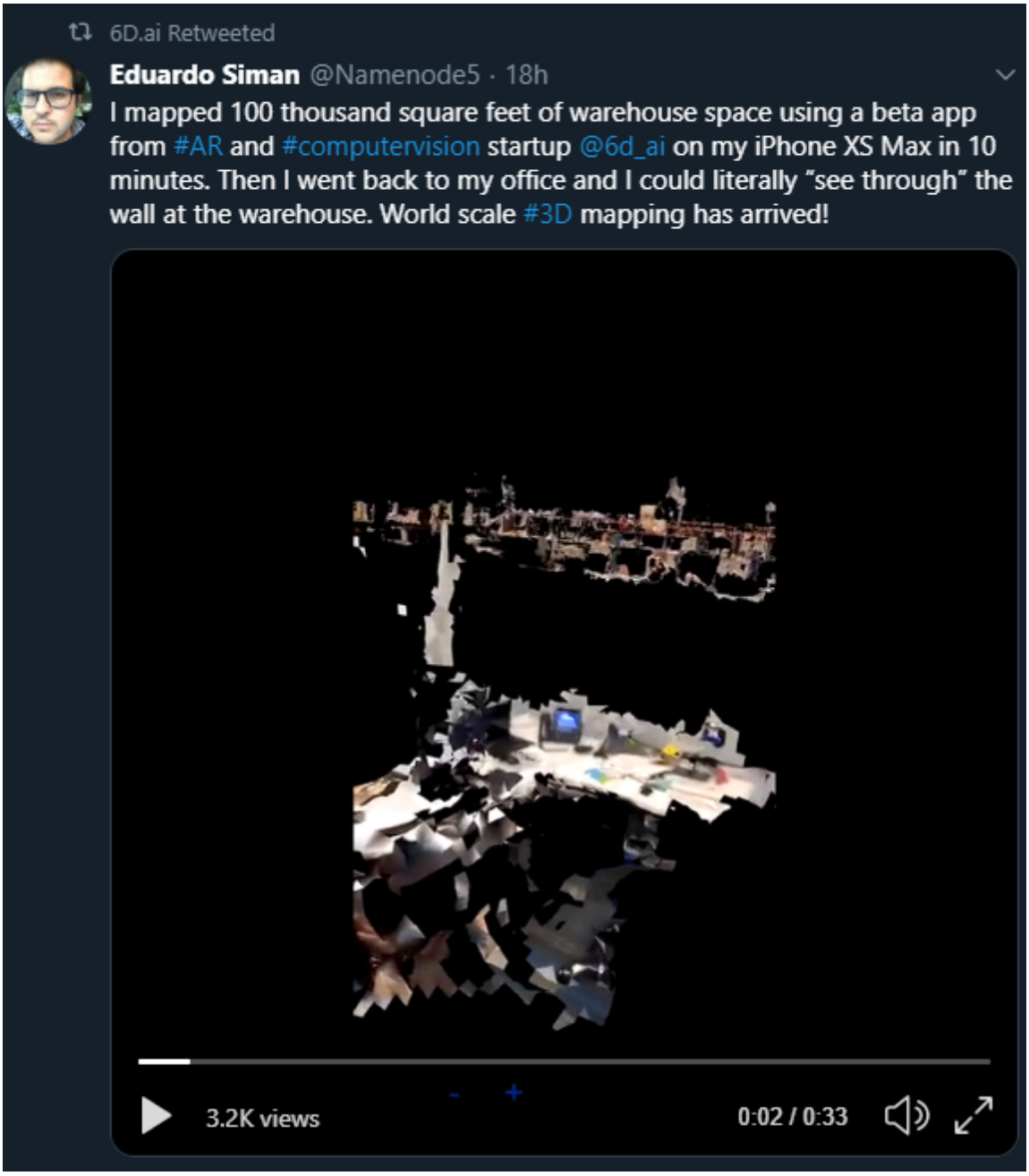


Figure 7.1: 6D.ai World Scale Mapping - An example of world-scale mapping using SLAM technology.

7.5.4 Photogrammetry Integration

Photogrammetry plays a significant role in creating realistic 3D assets for XR experiences. These photogrammetry-based models can be integrated into virtual environments to create more authentic and detailed scenes.

Once you've made the initial investment—learning the workflow, acquiring equipment like drones, and mastering the associated software—you can create detailed 3D models for VR/AR applications in real-world settings.

7.5.5 Challenges in Reality Integration

Integrating captured reality into XR experiences comes with several challenges:

1. **Data Processing**: Handling large amounts of captured data in real-time.
2. **Seamless Blending**: Ensuring that real and virtual elements blend naturally.
3. **Real-time Performance**: Maintaining high frame rates and low latency for immersive experiences.
4. **Lighting and Shadows**: Matching virtual lighting to real-world conditions.
5. **Occlusion Handling**: Correctly handling cases where real objects should occlude virtual ones and vice versa.

7.5.6 Future Directions

As reality capture and XR technologies continue to evolve, we can expect to see:

1. More seamless integration of real and virtual elements
2. Improved real-time performance for complex captured environments
3. Enhanced collaborative experiences in shared AR environments
4. More sophisticated use of AI for understanding and interacting with captured reality

7.5.7 Conclusion

Integrating captured reality into XR experiences represents a frontier in creating truly immersive and realistic virtual environments. By combining various reality capture techniques with advanced XR technologies, developers can create experiences that blur the line between the real and virtual worlds. As these technologies continue to advance, we can expect to see increasingly sophisticated and seamless integrations of captured reality in XR applications across various industries.

7.6 Ethics and Privacy in Reality Capture

Reality capture technologies raise significant ethical and privacy considerations that you need to keep in mind when developing XR experiences. The ability to capture detailed 3D representations of environments and people, combined with the potential for unintended bystander capture and the large amounts of sensitive data generated, creates responsibilities around consent, data security, and representation.

Key considerations include:

- **Consent protocols**: Ensuring individuals who may be captured are aware and have given informed permission, particularly challenging with technologies like 360-degree cameras and photogrammetry in public spaces
- **Bystander privacy**: Addressing unintended capture of people who haven't consented, especially when using tools that stream data to cloud services
- **Data governance**: Implementing secure storage, clear retention policies, and appropriate access controls for captured data
- **Representation and bias**: Being mindful of what you choose to capture and preserve, avoiding stereotypes, and respecting cultural sensitivities
- **Authenticity**: Maintaining transparency about what has been captured versus digitally altered, particularly important when photorealistic capture combined with AI enables sophisticated manipulation

The comprehensive discussion of privacy, consent, data governance, representation, and best practices for ethical reality capture can be found in Chapter 10. That chapter also addresses emerging concerns around deepfakes and manipulated reality, regulatory compliance requirements like GDPR, and frameworks for responsible development of reality capture applications.

7.7 Further Reading

Chapter 7 focused on the various techniques and technologies used to capture real-world environments and objects for use in XR applications. We explored methods such as photogrammetry, 3D scanning, volumetric video capture, and light field technology. The chapter also covered the integration of captured reality into XR experiences and the ethical considerations surrounding these practices. To deepen your understanding of reality capture and its applications in XR, consider the following resources:

- Reality Capture (from Epic): https://www.capturingreality.com/
  - Home of the Reality Capture photogrammetry application from Epic Games.

- Capturing Reality Community: https://dev.epicgames.com/community/capturing-reality
  - Community forum discussing various aspects of reality capture technologies and techniques.

8 Artificial Intelligence in XR Technologies

8.1 Introduction to AI in Immersive Media

Artificial Intelligence (AI) is increasingly becoming an integral part of Extended Reality (XR) technologies, enhancing the capabilities and user experiences of virtual, augmented, and mixed reality applications. This chapter explores the intersection of AI and XR, highlighting how machine learning and intelligent systems are shaping the future of immersive technologies.

Key areas where AI is making an impact in XR include:

1. Computer vision for improved tracking and environment mapping
2. Natural language processing for more intuitive voice interactions
3. Machine learning for adaptive and personalized experiences
4. AI-driven physics simulations for more realistic virtual environments

As we venture further into the digital age, the convergence of artificial intelligence, the metaverse, and immersive technologies is becoming increasingly significant. This convergence is reshaping how we interact with digital content and environments, offering new possibilities for human-computer interaction and digital world creation.

This natural and human interface that VR and AR makes possible creates digital worlds where it's easier to populate environments with artificial intelligence and create smarter, more responsive spaces.

This shift towards more intuitive, immersive interfaces presents an alternative to the increasing presence of robots in our physical spaces. Instead, it allows humans to interact more naturally with digital content and AI-driven entities within virtual environments.

8.2 AI-Generated Environments and Objects

One of the most exciting developments in this field is the use of AI to generate and populate virtual environments. This addresses a significant challenge in VR development.

These AI tools provide us with more advanced capabilities to create rich and interesting virtual worlds—addressing what has been holding back VR applications, namely the significant effort required to develop compelling virtual environments.

8.2.1 AI-Generated 360° Worlds

AI is now capable of generating entire 360° environments that users can explore in virtual reality.These AI-created worlds go beyond static images, incorporating depth information to create fully navigable 3D spaces.

YouTube Video

AI-Generated 360° Virtual Environments
Explore how artificial intelligence creates fully navigable 3D worlds with depth information, demonstrating the future of AI-powered content generation for immersive virtual reality experiences and automated world-building.
Watch at: https://www.youtube.com/watch?v=Q3KgkO0W1-4&t=s

8.2.2 Roblox's AI Integration

Roblox, a popular platform for creating and sharing virtual experiences, is at the forefront of integrating AI into world-building tools. Their "Chat to Create" feature allows users to verbally describe objects and environments they want to create.

You can essentially converse with these AIs and describe what you want: "I want a fireplace here, a bear there, and I want it to be in armor." The AI generates these elements, allowing you to build out virtual environments through conversation—environments you can then invite others to experience and share.

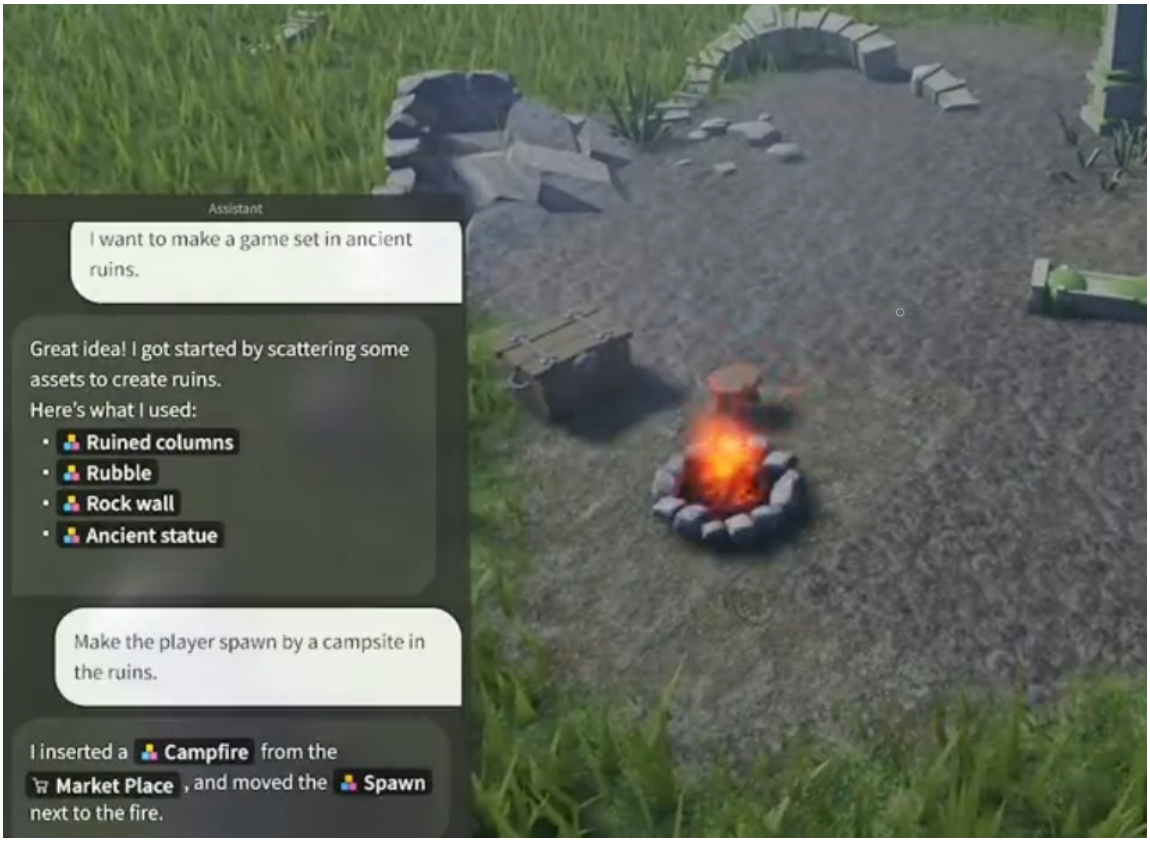


Figure 8.1: Roblox's AI-powered object creation interface.

This technology democratizes the creation of virtual worlds, allowing users with no programming or 3D modeling experience to bring their imaginations to life through simple conversation with an AI.

8.2.3 AI-Generated 3D Objects

The capabilities of AI in 3D content creation extend to individual objects as well. Tools like DreamCraft3D allow users to generate detailed 3D models simply by providing a text description.

By simply writing a text description of what you want, you can generate a fully 3D virtual object that can populate your virtual environments or be placed in real environments through augmented reality.

This technology has wide-ranging applications, from populating virtual worlds with unique objects to creating AR experiences where AI-generated models can be placed in the real world through a device's camera.

YouTube Video

DreamCraft3D Text-to-3D Generation
Witness AI technology that transforms text descriptions into detailed 3D objects and models, showcasing applications for populating virtual worlds and creating AR experiences with AI-generated content from simple prompts.
Watch at: https://www.youtube.com/watch?v=0FazXENkQms&t=s

8.2.4 Implications for XR Development

The integration of AI-generated content in XR environments has several significant implications:

1. **Rapid Prototyping**: Developers can quickly generate and iterate on virtual environments and objects.
2. **Personalization**: AI can create custom environments and objects based on user preferences or specific requirements.
3. **Scalability**: The ability to generate content algorithmically allows for the creation of vast, diverse virtual worlds.
4. **Accessibility**: Non-technical users can participate in content creation, potentially leading to more diverse and creative XR experiences.

As AI technologies continue to advance, we can expect even more sophisticated and seamless integration of AI-generated content in XR applications, further blurring the lines between human-created and AI-generated virtual worlds.

8.3 Generative 3D Pipelines and Interactive Worlds

The past year has produced a clearer pipeline for moving from prompts to explorable spatial experiences. Successful teams treat generative systems as modular stages that can be swapped or repeated depending on the fidelity targets.

8.3.1 Pipeline Overview (2025)

1. **Prompting & Concept Capture**: Start with text, sketches, or reference images. Platforms such as World Labs' Marble accept plain-language prompts and return explorable 3DGS scenes.(World Labs 2024)
2. **Intermediate Video or Scene Generation**: Systems like Odyssey's interactive video demos and DreamInteractive's UE5 workflows generate cinematic flythroughs or layout videos that double as validation passes.(Odyssey Studios 2024; DreamInteractive 2024)
3. **3D Asset Materialization**: Choose output modalities—Gaussian splats, meshes, or hybrid representations. Genie 3 and TRELLIS-style research models offer toggles between splats and meshes; DreamInteractive demonstrates mesh handoffs to Unreal Engine.(Qian et al. 2024; DreamInteractive 2024)
4. **Engine Import & Interaction Layer**: Bring assets into Unity or Unreal, add lighting, physics, and interactions, and connect to multiplayer or analytics services.
5. **Deployment & Iteration**: Test the experience on target hardware, gather telemetry, and feed findings back into the prompt or editing stages.(World Labs 2024; Decart AI 2024)

⚠ Current limitations to plan around

- **Temporal coherence**: Video-first outputs (e.g., Odyssey) still struggle with shot-to-shot continuity; expect to curate sequences manually.(Odyssey Studios 2024)
- **Physics and affordances**: Generated worlds rarely include collision volumes or gameplay logic—teams must author these layers post-import.
- **Texture fidelity & scale**: Mesh exports can arrive with stretched UVs or inconsistent scale; always validate measurements before interactive deployment.
- **Cost envelopes**: Cloud-based systems (Marble, Decart-XR) meter GPU time; budget for iteration passes when scoping projects.(World Labs 2024; Decart AI 2024)

8.3.2 Import Checklists

Whether the output is a splat or a mesh, keep a standing checklist before you promise interactivity:

1. **Coordinate alignment**: Normalize scene scale and orientation so generated spaces align with engine units.

2. **Lighting strategy**: Decide between baked lighting, real-time global illumination, or emissive splats; World Labs scenes often ship with lighting baked into textures.
3. **Interaction shells**: Add invisible collision meshes or navmeshes for locomotion. DreamInteractive's UE5 demos illustrate wrapping generated geometry with simplified colliders for traversal.
4. **Accessibility hooks**: Pair AI-generated layouts with hand-authored UI, captions, and locomotion options before shipping.

8.3.3 Case Spotlights

- **World Labs Marble**: Prompt-to-3DGS restaurant scenes stream directly to browsers and Vision Pro, showcasing rapid ideation.(World Labs 2024)
- **DreamInteractive UE5 Workflow**: Uses generative passes to block out spaces, then layers Unreal assets for gameplay—ideal for hybrid AI/manual teams.(DreamInteractive 2024)
- **Genie 3 Analyses**: Research deep dives explain how structured latents unlock mesh or splat outputs from the same prompt, guiding pipeline decisions.(Qian et al. 2024)
- **Decart-XR**: Real-time passthrough transformation on Quest illustrates how AI-generated visual styles can be interactive, not just static captures.(Decart AI 2024)

8.4 AI-Driven Characters and Interactions

As AI technologies advance, they are revolutionizing the way we create and interact with virtual characters in XR environments. From intelligent non-player characters (NPCs) to virtual assistants, AI is enabling more natural, responsive, and engaging interactions in immersive experiences.

8.4.1 Virtual AI Agents

Virtual AI agents are becoming increasingly sophisticated, offering personalized interactions within virtual environments. A prime example of this technology is demonstrated in a golf game featuring an AI caddy named Arthur.

Figure 8.2: An AI golf caddy named Arthur, offering personalized coaching in a virtual golf environment. Golf+ on Meta Quest

In this application, users can engage in natural language conversations with Arthur, who serves as both a caddy and coach. The AI agent utilizes advanced language understanding and generation capabilities to provide contextually relevant advice and information about the golf courses.

The virtual caddy introduces himself naturally: "Hello there. My name is Arthur, and I'll be your personal caddy and coach. What would you like me to call you?"

This level of personalization and interactivity showcases the potential for AI agents to enhance user experiences in virtual environments. However, it's worth noting that the widespread implementation of such sophisticated AI interactions may still be limited by computational costs.

However, I'm not certain if this technology is widely released yet. One limiting factor is that these AI systems are still rather expensive to operate, which may be holding back broader implementation in consumer applications.

View the AI Golf Guide demo on Twitter

8.4.2 Large Language Models in XR

The integration of large language models (LLMs) like GPT-3 and its successors into XR environments is opening up new possibilities for creating intelligent, context-aware virtual characters. These models can:

1. Generate dynamic dialogue based on user interactions and the current context.
2. Adapt character behavior to user preferences and past interactions.
3. Provide real-time language translation and cultural context in virtual environments.

8.4.3 Emotional and Contextual Awareness

Advanced AI systems are being developed to recognize and respond to users' emotional states and contextual cues within XR environments. This includes:

- Facial expression recognition to adapt character responses
- Voice tone analysis for more nuanced interactions
- Body language interpretation for more natural social interactions

These technologies have the potential to create more empathetic and responsive virtual characters, enhancing the overall immersion and engagement in XR experiences.

8.5 AI in Content Creation and Storytelling

AI is not only changing how we interact with virtual environments but also how we create content and tell stories within these spaces. From procedurally generated worlds to AI-assisted narrative design, the possibilities are expanding rapidly.

8.5.1 AI-Generated Movies and Immersive Narratives

The realm of content creation is being revolutionized by AI-generated movies and narratives. These productions are entirely produced by artificial intelligence, from script to visuals, showcasing the immense potential of AI in creative industries.

YouTube Video

Sora AI Video Generation Demo
OpenAI's groundbreaking text-to-video model creating highly realistic video content from text descriptions, revolutionizing content creation for immersive experiences and demonstrating the future of AI-powered narrative generation for XR applications.
Watch at: https://www.youtube.com/watch?v=HK6y8DAPN_0&t=s

Several platforms and models are at the forefront of this technology:

1. Pika: An AI-powered platform for creating and editing videos.
2. Stable Video Diffusion: An open-source AI model for video generation and editing.
3. Sora: OpenAI's text-to-video model, capable of generating highly realistic video content from text descriptions.

These tools are pushing the boundaries of what's possible in digital content creation, allowing for the rapid production of complex, high-quality video content without traditional filming and editing processes.

8.5.2 AI-Assisted World Building

The concept of AI-assisted world building is bridging the gap between imagination and reality in virtual environments. While not yet fully realized, the potential for AI to assist in creating complex, dynamic virtual worlds is immense.

AI-assisted world building could potentially allow creators to:

1. Generate detailed environments from high-level descriptions
2. Dynamically adjust and expand virtual worlds based on user interactions
3. Create consistent and believable ecosystems within virtual spaces

This technology could dramatically reduce the time and resources required to create large-scale virtual environments, making it possible for smaller teams or even individual creators to build vast, immersive worlds.

8.5.3 Procedural Content Generation

AI-driven procedural content generation is already being used in many games and virtual environments to create diverse and seemingly endless content. This includes:

- Terrain generation for expansive virtual landscapes
- Dynamic NPC behavior and dialogue
- Adaptive music and sound effects that respond to user actions and environment

As AI technologies continue to advance, we can expect even more sophisticated procedural generation techniques that create not just individual elements, but entire coherent and richly detailed virtual worlds.

8.5.4 Implications for XR Storytelling

The integration of AI in content creation and storytelling for XR has several important implications:

1. **Personalized Narratives**: AI could adapt stories and environments in real-time based on user preferences and actions.
2. **Infinite Content**: AI-generated content could provide endless variations of experiences within a single XR application.
3. **Collaborative Creation**: AI could serve as a creative partner, assisting human creators in developing more complex and nuanced virtual worlds and narratives.
4. **Accessibility**: AI-assisted creation tools could make it easier for non-technical users to create sophisticated XR content.

As these AI technologies continue to evolve, they promise to unlock new possibilities for expression, learning, and experience across a wide range of XR applications, potentially transforming how we create and consume immersive content.

8.6 AI for XR Development and Optimization

Artificial Intelligence is not only enhancing the content and interactions within XR environments but also revolutionizing the development process itself. From optimizing performance to enhancing rendering techniques, AI is becoming an indispensable tool for XR developers.

8.6.1 Performance Optimization

AI algorithms are being employed to optimize the performance of XR applications in real-time. This includes:

1. **Dynamic Level of Detail (LOD)**: AI can adjust the complexity of rendered objects based on their importance and the device's performance capabilities.
2. **Predictive Loading**: AI algorithms can predict user movements and pre-load relevant content, reducing latency and improving immersion.
3. **Adaptive Resolution Scaling**: AI can dynamically adjust rendering resolution to maintain frame rates while maximizing visual quality.

These optimizations are crucial for maintaining the high frame rates and low latency required for comfortable XR experiences, especially on mobile devices or standalone headsets with limited processing power.

8.6.2 Machine Learning for Gesture and Voice Recognition

Advanced machine learning models are enhancing the way users interact with XR environments through gestures and voice commands.This section focuses on AI-driven improvements to recognition technologies, while foundational gesture and voice recognition principles, implementation techniques, and design best practices are covered in Section 5.8.

1. **Gesture Recognition**: AI models can recognize complex hand gestures and body movements, allowing for more natural and intuitive interactions in VR and AR.
2. **Voice Commands**: Natural Language Processing (NLP) models enable sophisticated voice control systems, allowing users to interact with virtual environments using natural speech.
3. **Multimodal Interaction**: AI can combine inputs from various sources (gesture, voice, eye-tracking) to interpret user intent more accurately.

These AI advancements are particularly important for creating accessible XR experiences and for scenarios where traditional input methods are impractical.

8.6.3 AI-in-the-Loop Workflows for Development

AI tools are now embedded throughout the XR production toolchain, helping teams ship faster while maintaining quality. Treat these assistants as collaborators that accelerate ideation, refactoring, and asset audits rather than full replacements for human expertise.

1. **Coding companions**: Engine-native assistants like Epic Developer Assistant surface Unreal documentation, write Blueprint snippets, and answer API questions in context. Pair these tools with automated tests to validate generated code before merging.(Epic Games 2024b)
2. **Rapid prototyping**: Workflows such as Claude Code's Three.js apartment build show how AI can scaffold entire webXR scenes from photo sets—useful for pitch decks or quick user tests.(Hernandez 2024)
3. **Search and refactor**: Integrate chat-based code explorers to trace input pipelines or render loops across large projects; this shortens onboarding for new teammates.
4. **Asset provenance**: Maintain a provenance log when importing AI-generated meshes or textures from tools like BlenderGPT and Meshy. Document prompts, sources, and licenses to ease compliance reviews.(BlenderGPT Team 2024; Meshy 2024)
5. **Continuous review**: Schedule human-in-the-loop checkpoints to confirm that AI suggestions respect performance budgets, accessibility requirements, and platform guidelines.

> **Workflow tip**
>
> Create a shared "AI usage register" for your team that tracks which assistants were used for code, art, or design decisions. This audit trail supports ethical sourcing discussions and helps debug regressions when a model update changes outputs.

8.6.4 AI-Enhanced Rendering Techniques

AI is also being used to improve the visual quality of XR experiences while maintaining performance:

1. **Neural Rendering**: Techniques like Neural Radiance Fields (NeRF) use AI to generate photorealistic 3D scenes from a set of 2D images.
2. **AI Upscaling**: Machine learning models can upscale lower-resolution renders to higher resolutions in real-time, reducing the computational load while maintaining visual quality.

3. **Intelligent Occlusion**: AI can predict and render realistic occlusions in AR applications, improving the integration of virtual objects into the real world.

Gaussian Splatting represents a particularly interesting development for creating photorealistic avatars that could become more readily available in XR applications.

While still in development, these AI-enhanced rendering techniques promise to significantly improve the visual fidelity and performance of XR applications.

8.6.5 Documenting AI Collaboration in Development

As AI tools become standard parts of XR development workflows, how you document their use becomes an important professional practice. This isn't about confession or compliance—it's about making your development process transparent, learnable, and reproducible.

What to Document: Process, Not Just Tools

Rather than simply listing AI tools used, document the development process and how AI collaboration shaped it:

- **Initial challenge**: What problem were you trying to solve or what feature were you implementing?
- **AI interaction**: What did you ask the AI? How did initial suggestions compare to what you needed?
- **Critical evaluation**: Where did AI suggestions work well? Where did you need to modify or reject them?
- **Iterative refinement**: How did the solution evolve through conversation with AI tools?
- **Final implementation**: How does your final code or design differ from initial AI outputs, and why?

This documentation demonstrates understanding and critical engagement, not just AI use.

XR Development Examples

Consider these concrete scenarios where documenting AI collaboration adds value:

Shader Development: You're implementing a custom shader for volumetric fog in your VR environment. An AI assistant suggests an approach, but you notice it doesn't account for stereo rendering. Your documentation might note: - Initial challenge: Performant volumetric fog for VR - AI suggestion: Standard single-pass volumetric approach - Your modification: Adapted for stereo rendering with single-pass instancing - Performance consideration: Reduced from AI's suggested quality level to maintain 90fps

This documentation helps future developers (including yourself) understand both the AI contribution and the XR-specific expertise you applied.

Locomotion Mechanics: When implementing teleportation movement, AI tools might suggest standard approaches. Your documentation captures: - How you modified AI suggestions to prevent motion sickness - Why you rejected certain AI recommendations based on comfort testing - How you iterated on the arc visualization based on user feedback - Platform-specific adaptations AI didn't initially consider

Interaction Pattern Design: For a hand-tracking interaction system, document: - Initial AI suggestions for gesture recognition thresholds - How play-testing revealed different needs for your specific use case - Adjustments made for accessibility (larger tolerance ranges, alternative inputs) - Integration challenges AI didn't anticipate when working with your specific SDK

Practical Implementation

You don't need elaborate systems. Effective documentation can be:

Project notes: Maintain a development journal noting significant AI interactions

```
2024-03-15: Used AI assistant to implement spatial audio occlusion
- Initial suggestion used standard raycasting
- Modified to use custom audio zones for performance
- Added fallback for devices without spatial audio support
```

Code comments: Note AI assistance and modifications directly in code

```
// Initial implementation suggested by AI assistant
// Modified to account for VR comfort constraints:
// - Reduced max velocity from 10 to 5 m/s
// - Added smoothing for direction changes
// - Implemented tunnel vision vignette
```

Methods sections: For projects with documentation or papers, include a brief methods note

```
The shader system implementation was developed in collaboration with AI
coding assistants. Initial approaches were iteratively refined based on
stereo rendering requirements and mobile VR performance constraints.
```

Design documentation: Note AI contributions to interaction design decisions

```
Navigation system:
- Teleportation mechanics: Base implementation from AI suggestion,
  modified for comfort based on playtesting
- Comfort options: Added independently based on accessibility research
- Platform adaptation: Quest-specific optimizations developed manually
```

When Documentation Matters Most

Documentation is particularly valuable when:

- Working in teams: Others need to understand design decisions and can learn from your AI collaboration process
- Educational contexts: Demonstrating your understanding and learning process
- Iterative projects: Future you needs to understand past decisions
- Novel implementations: Others facing similar challenges can learn from your approach
- Quality assurance: Teams need to trace why certain approaches were chosen

What This Achieves

Good documentation of AI collaboration: - Demonstrates critical thinking and understanding - Makes development process reproducible and learnable - Supports knowledge transfer within teams - Shows where domain expertise (XR-specific knowledge) complemented AI suggestions - Creates audit trails for decision-making

This documentation practice positions AI as what it should be: a tool that amplifies your expertise rather than replaces it. The documentation shows not just that you used AI, but how you applied your XR knowledge to evaluate, refine, and improve AI suggestions.

For broader ethical and professional considerations around AI collaboration, see Chapter 10.

8.7 Ethical Considerations in AI-Powered XR

The integration of AI into XR technologies raises significant ethical considerations that you need to address in your development practices. AI systems in XR collect unprecedented amounts of user data—including biometric signals, gaze patterns, room layouts, and behavioral information—creating substantial privacy and consent responsibilities. Ambient AI companions may continuously observe private settings, while AI-generated content can perpetuate biases present in training data, leading to unfair treatment or stereotypical representations.

Key considerations for AI in XR include:

- **Privacy and data governance**: Managing the scope of data collection, cloud processing implications, consent for spatial recordings, and GDPR compliance
- **Bias and fairness**: Ensuring AI systems don't discriminate, auditing generated content for cultural sensitivity, and addressing accessibility gaps for underrepresented groups
- **Transparency in AI collaboration**: Documenting how AI tools are used in development (covered in Section 8.6.5)
- **User wellbeing**: Balancing AI capabilities with authentic human experiences, addressing uncanny valley effects, and ensuring users maintain agency

Emerging concerns include brain-computer interfaces raising new neural privacy questions, emotional AI creating manipulation risks, and the authenticity of AI-generated immersive experiences. As AI systems become more sophisticated—enabling autonomous virtual worlds, advanced emotional recognition, and enhanced haptics—the ethical framework for their deployment becomes increasingly important.

The comprehensive treatment of these issues, including practical implementation checklists, bias mitigation strategies, and ethical frameworks for AI-powered XR development, can be found in Chapter 10. That chapter also addresses the broader context of how AI ethics intersects with XR's unique privacy challenges, the psychological impacts of AI-driven experiences, and best practices for responsible development.

8.8 Further Reading

Chapter 8 explored the integration of Artificial Intelligence (AI) with XR technologies, covering topics such as AI-generated environments and objects, AI-driven characters and interactions, AI in content creation and storytelling, and the use of AI for XR development and optimization. We also discussed ethical considerations and future directions for AI in XR. To further your understanding of this rapidly evolving field, consider these resources:

8.8.1 Additional Resources

- NVIDIA AI & VR Research: https://www.nvidia.com/en-us/research/ai-playground/
  - Showcases cutting-edge research at the intersection of AI and XR technologies.
- OpenAI News: https://openai.com/news/

  - While not specific to XR, it provides insights into the latest AI developments, many of which have potential XR applications.

- MIT Technology Review - Artificial Intelligence: https://www.technologyreview.com/topic/artificial-intelligence/
  - Offers articles and analysis on the latest developments in AI, including applications in XR.

9 Further Reading

9.1 Books

- Bailenson, J. (2018). Experience on Demand: What Virtual Reality Is, How It Works, and What It Can Do. W. W. Norton & Company.
- Jerald, J. (2015). The VR Book: Human-Centered Design for Virtual Reality. Association for Computing Machinery and Morgan & Claypool Publishers.

9.2 Research Papers

- Somanath, S., et al. (2024). Towards Urban Digital Twins: A Workflow for Procedural Visualization Using Geospatial Data. Remote Sensing, 16(11), Article 11.
- Stahre Wästberg, B., et al. (2017). Visualizing Environmental Data for Pedestrian Comfort Analysis in Urban Planning Processes. In Proceedings of CUPUM 2017.

9.3 Examples and Case Studies

- Digital Twin City Center (DTCC) Milestone Projects
- CityAirSim Project

9.4 AI recommendations

Check before use!

9.4.1 Papers

- Risi, S., & Togelius, J. (2020). Increasing generality in machine learning through procedural content generation. Nature Machine Intelligence, 2(8), 428-436.
  - Explores the use of AI for generating content in virtual environments.
- Zhu, J. Y., Park, T., Isola, P., & Efros, A. A. (2017). Unpaired image-to-image translation using cycle-consistent adversarial networks. In Proceedings of the IEEE international conference on computer vision (pp. 2223-2232).
  - Explores AI techniques for generating and transforming visual content, relevant to XR applications.

10 Societal Impact and Ethical Design

As immersive technologies become more sophisticated and widespread, you need to consider their psychological, social, and ethical implications. This chapter explores the key factors that XR developers and researchers should keep in mind when creating immersive experiences. The goal is not to provide prescriptive rules, but rather to highlight considerations that should inform your design decisions and development practices.

10.1 Psychological Impact and Virtual Embodiment

The ability of XR systems to manipulate our sense of body ownership and self-perception carries profound implications. As discussed in Section 1.4, the rubber hand illusion and body ownership experiments demonstrate how easily our brains accept virtual bodies as our own. This plasticity creates both opportunities and responsibilities.

10.1.1 Implications of Body Ownership Manipulation

When users embody avatars of different sizes, races, or genders, their behavior and self-perception can change. The Proteus Effect shows that avatar appearance influences user behavior—people with taller avatars may negotiate more aggressively, while embodying avatars of different races can affect implicit bias. Research has even demonstrated that virtual embodiment can influence cognitive performance and self-efficacy.

You need to consider:

- **Psychological safety**: How might extended virtual embodiment affect users' sense of self and body image?
- **Therapeutic applications**: While virtual embodiment shows promise for treating conditions like phantom limb pain or body dysmorphia, these applications require careful clinical oversight.
- **Identity exploration**: XR can provide valuable spaces for identity exploration, but designers should be mindful of potential psychological impacts from prolonged or intense embodiment experiences.

- **Age-appropriate design**: The malleability of body perception may be particularly significant for younger users whose self-concepts are still developing.

10.1.2 Self-Perception and Behavioral Change

The finding that virtual embodiment can alter math performance, racial attitudes, and other cognitive and social factors demonstrates the power of these technologies. This power requires thoughtful application. Consider whether your XR experience might inadvertently reinforce stereotypes or create unintended psychological effects through avatar design and embodiment mechanics.

10.2 Privacy, Consent, and Data Governance

XR systems capture unprecedented amounts of personal data. Modern headsets track gaze direction, hand movements, body position, room layouts, and increasingly, biometric signals. This data reveals not just what users do, but how they move, where they look, and potentially what captures their attention or causes emotional responses.

10.2.1 The Scope of XR Data Collection

Unlike traditional computing interfaces, XR devices can capture:

- **Biometric data**: Gaze patterns, pupil dilation, heart rate variability
- **Spatial data**: Room layouts, furniture placement, environmental features
- **Behavioral data**: Movement patterns, reaction times, interaction preferences
- **Bystander data**: Unintended capture of people who happen to be in the environment
- **Passthrough imagery**: Real-world video feeds in mixed reality applications

10.2.2 Consent and Transparency

You need to consider several dimensions of consent in XR:

Active vs. passive capture: Users may consent to wearing a headset but not fully understand the scope of data collection. Clear communication about what sensors are active and what data is being collected is fundamental.

Bystander consent: When using passthrough video or reality capture in public or shared spaces, others may appear in your captured data without their knowledge or consent. Tools

like Horizon Hyperscape that stream sensor data to cloud services for processing create particular challenges for bystander privacy.

Purpose limitation: Users should understand not just what data is collected, but how it will be used, who will have access, and how long it will be retained.

Withdrawal of consent: Provide clear mechanisms for users to delete their data, stop collection, or export their information.

10.2.3 GDPR and Regulatory Compliance

XR data collection often falls under regulations like GDPR in Europe or CCPA in California. You need to:

- Map every data type collected to its legal basis before deployment
- Obtain explicit consent for persistent spatial recordings
- Provide deletion workflows for captured spaces and avatars
- Redact or blur bystanders by default when streaming passthrough video
- Maintain export logs tracking where data is stored and who accessed it

10.2.4 Cloud Processing and Data Residency

Many XR capture tools stream raw sensor data to cloud services for reconstruction or processing. This creates questions about data retention, residency, and security. When using platforms that rely on cloud processing, understand:

- Where your data is processed and stored
- What the service provider's data retention policies are
- Whether you can specify data residency requirements
- What happens to your data if you stop using the service

10.2.5 Ambient AI and Always-On Sensing

AI companions and assistants in mixed reality may continuously observe private settings and conversations. When implementing ambient AI features:

- Communicate clearly when recording is active
- Offer privacy modes that pause sensors on demand
- Provide visual or audio indicators of sensing state
- Allow users to review and delete interaction histories

10.3 Bias, Fairness, and Representation

AI systems and captured reality can perpetuate or amplify existing biases. In XR contexts, this manifests in several ways that you should consider during development.

10.3.1 Bias in AI-Generated Content

When using AI to generate virtual environments, characters, or avatars, the training data's biases may appear in your application:

- **Representation**: AI-generated characters and environments may lack diversity or rely on stereotypical representations
- **Cultural assumptions**: Generated content may reflect cultural biases from training data
- **Accessibility**: AI systems may not adequately consider users with different abilities

Before deploying AI-generated content, audit it for cultural sensitivity and diverse representation. Consider involving community review, particularly when creating content that represents cultures or communities you're not part of.

10.3.2 Bias in Reality Capture

Photogrammetry, 3D scanning, and other reality capture techniques raise representation concerns:

- **Selection bias**: What you choose to capture and preserve reflects decisions about what's valuable or important
- **Access bias**: Not all communities have equal access to reality capture technologies or the ability to preserve their environments digitally
- **Interpretation**: How captured spaces are presented and contextualized can reinforce or challenge existing narratives

10.3.3 Algorithmic Fairness

AI systems in XR may treat users differently based on characteristics inferred from their behavior or biometric data:

- **Recognition accuracy**: Gesture and voice recognition systems may perform differently for users of different ages, genders, or cultural backgrounds

- **Adaptive systems**: AI that personalizes experiences based on user data may inadvertently create discriminatory outcomes
- **Training data diversity**: Ensure systems are trained on diverse datasets that represent your intended user population

10.3.4 Inclusive Design Practices

To mitigate bias and ensure fairness:

- Test your XR experiences with diverse user groups throughout development
- Involve people from underrepresented communities in design decisions
- Audit AI systems for differential performance across demographic groups
- Provide multiple interaction modalities to accommodate different preferences and abilities
- Be transparent about system limitations and known biases

10.4 Accessibility and Inclusive Design

XR technologies present both opportunities and challenges for accessibility. You need to consider how your experiences can be made accessible to users with varying physical, sensory, and cognitive abilities.

10.4.1 Physical Accessibility

XR systems often assume certain physical capabilities:

Mobility: Many VR experiences assume users can stand, walk, or make large gestures. Consider: - Seated play modes that don't require standing or room-scale movement - Alternative navigation methods beyond physical walking - Customizable interaction zones that accommodate different reach ranges - Support for assistive devices and mobility aids

Manual dexterity: Hand tracking and controller-based interactions may not work for all users: - Provide alternative input methods (voice, gaze, simplified gestures) - Allow customization of gesture sensitivity and timing - Support adaptive controllers and assistive input devices - Avoid requiring fine motor control for critical interactions

10.4.2 Sensory Accessibility

Vision: Not all users have full visual capability: - Provide audio descriptions and spatial audio cues - Support screen readers and text-to-speech where applicable - Allow customization of visual elements (contrast, size, motion) - Consider colorblind-friendly design choices - Offer haptic feedback as an alternative information channel

Hearing: Audio-dependent experiences exclude users with hearing impairments: - Provide captions and visual indicators for audio cues - Use visual and haptic alternatives to spatial audio navigation - Ensure important information isn't conveyed solely through sound - Support hearing aid compatibility and audio customization

10.4.3 Cognitive Considerations

While comprehensive cognitive accessibility is beyond this chapter's scope, you should be aware that users process information differently. Consider providing options for adjusting information density, interaction pacing, and complexity of decision-making to accommodate different cognitive processing styles.

10.4.4 Designing for Inclusion

Accessibility is not a retrofit—it should inform design from the beginning:

- Follow established accessibility guidelines (WCAG, XR Access guidelines)
- Test with users who have different abilities throughout development
- Provide extensive customization options rather than one-size-fits-all experiences
- Document accessibility features so users know what accommodations are available
- View accessibility as expanding your potential audience, not limiting design

10.5 Emerging Concerns

As XR technologies advance, new ethical challenges emerge that you should monitor and consider in your development practices.

10.5.1 Deepfakes and Manipulated Reality

Reality capture technologies combined with AI create possibilities for sophisticated manipulation:

Authenticity concerns: When photorealistic virtual environments and characters become indistinguishable from captured reality, questions arise about: - How users can verify the authenticity of experiences - The potential for creating misleading or false immersive content - Applications in journalism, historical preservation, and documentation where accuracy matters

Volumetric deepfakes: Volumetric capture combined with AI could enable creation of convincing but fabricated recordings of people: - Consider watermarking or provenance tracking for captured content - Be transparent about what elements of an experience are captured versus generated - Maintain integrity in applications where authenticity is important

10.5.2 Brain-Computer Interfaces and Neural Data

Advanced XR systems may incorporate brain-computer interfaces, raising new privacy and consent considerations:

- **Neural data**: Brain activity patterns reveal cognitive and emotional states in ways users may not fully understand or control
- **Cognitive liberty**: As systems potentially influence thought patterns or emotional states, questions of autonomy and manipulation arise
- **Unintended inference**: Neural data might reveal information users didn't intend to share

10.5.3 Emotional AI and Affective Computing

Systems that recognize and respond to emotional states create both opportunities and concerns:

- **Emotional manipulation**: Understanding users' emotional states could enable experiences that manipulate rather than enhance
- **Emotional privacy**: Users may not want their emotional responses captured or analyzed
- **Consent for emotional data**: The sensitivity of emotional information requires particularly clear consent

10.5.4 Digital Rights and Ownership

As users create content and spend time in virtual spaces, questions of ownership and rights emerge:

- **User-generated content**: Who owns virtual objects, spaces, or experiences users create?
- **Virtual property**: What rights do users have to their virtual possessions or achievements?
- **Persistent identities**: As virtual identities become more important, what rights do users have to their avatars and digital presence?
- **Right to deletion**: Can users truly delete their presence and data from persistent virtual worlds?

10.5.5 Environmental and Social Impact

The infrastructure supporting XR has real-world consequences:

Energy consumption: Cloud processing, AI training, and continuous rendering require significant energy: - Consider the environmental cost of computationally expensive features - Optimize for efficiency where possible - Be transparent about the environmental footprint of XR services

Social dynamics: Immersive technologies may affect how people relate to each other: - Monitor for potential isolation or over-reliance on virtual interaction - Consider how XR might affect in-person social skills, particularly for young users - Design for balance between virtual and physical experiences

10.6 Transparent AI Collaboration and Learning

As AI tools become integral to XR development and content creation, how we document and communicate about this collaboration becomes an ethical consideration. This applies to all XR practitioners—from students learning development to professional teams shipping products.

10.6.1 Reframing AI Use

Rather than treating AI assistance as something to confess or hide, consider it as a collaboration to document and make visible. The question shifts from "Did you use AI?" to "How did you collaborate with AI, and what did you learn from that process?"

This reframing recognizes that: - AI tools are becoming standard parts of the development toolkit - The skill lies in knowing how to use these tools effectively - Documenting the collaboration process demonstrates understanding - Transparency supports learning and methodological development

10.6.2 Thought Partner vs. Thought Substitute

A critical distinction exists between using AI as a thought partner versus a thought substitute:

Thought partner: You engage with AI iteratively, questioning outputs, refining prompts, and applying critical judgment: - Initial challenge or question you're working through - Key insights or suggestions AI provides - Where you disagree, modify, or build on AI suggestions - How the final implementation differs from initial AI outputs and why

Thought substitute: Accepting AI outputs without engagement or understanding: - Taking first outputs without iteration or refinement - Implementing suggestions without understanding how they work - Unable to explain or modify the AI-generated solutions

The value lies not in the AI's first response, but in the iterative conversation and refinement process. This engagement demonstrates understanding and develops capability.

10.6.3 Making Collaboration Visible and Learnable

When you document your AI collaboration process, you: - Make your learning process visible to others - Create records that help you understand your own development - Demonstrate critical engagement rather than passive acceptance - Contribute to collective understanding of effective AI use

For students and learners, this documentation becomes part of demonstrating understanding. For professional teams, it supports knowledge transfer and quality assurance.

10.6.4 Professional Practice and Lifelong Learning

This applies beyond educational contexts. Professional XR development increasingly involves AI tools: - Code generation assistants that suggest implementation approaches - Asset creation tools that generate 3D models or textures - Design assistants that propose interaction patterns

Professional practice means documenting these collaborations: - What AI tools were used at what stages - How their outputs were evaluated and modified - What design decisions were informed by AI suggestions versus human judgment

This documentation serves quality assurance, supports team communication, and maintains accountability in professional contexts.

10.6.5 Practical Approaches

You don't need complex systems to document AI collaboration. Consider:

- **Project notes**: Maintain working notes about AI interactions during development
- **Methods documentation**: Include AI assistance in technical documentation
- **Conversation logs**: Keep records of significant AI interactions for reference
- **Decision logs**: Note when AI suggestions were accepted, modified, or rejected and why

The goal is making the collaboration process transparent and learnable, not creating administrative burden.

For practical methods of documenting AI collaboration in XR development workflows, see Section 8.6.5.

10.7 Ethical Framework for XR Developers

Rather than providing prescriptive rules, this framework offers questions and considerations to inform your development decisions.

10.7.1 Design-Stage Considerations

When beginning an XR project, consider:

User wellbeing: - Could this experience cause physical discomfort or harm? - What psychological impacts might prolonged use have? - Are there vulnerable populations for whom this experience might be problematic?

Data and privacy: - What data does this experience need to collect? - Is the data collection proportional to the value provided? - How will you handle consent, especially for bystander data? - What's your data retention and deletion policy?

Accessibility: - Who might be excluded by your current design? - What alternative interaction methods could broaden access? - Are you designing for customization and user preference?

Representation: - If using AI-generated content, have you audited it for bias? - Does your experience reflect diverse perspectives and representations? - Have you consulted with communities your experience represents?

10.7.2 Implementation-Stage Considerations

During development, regularly review:

Technical implementation: - Are you implementing data collection with appropriate security? - Does your system handle user consent properly? - Have you provided privacy controls and transparency features? - Are accessibility features integrated or retrofitted?

Testing and validation: - Are you testing with diverse user groups? - Have you validated that accessibility features work as intended? - Are you monitoring for unintended consequences or edge cases?

AI and automation: - If using AI systems, do you understand their limitations and biases? - Have you documented your AI collaboration process? - Can you explain how AI-generated elements work and were validated?

10.7.3 Deployment and Ongoing Considerations

Once deployed, continue monitoring:

User feedback: - Are users experiencing your application as intended? - Are there reports of discomfort, exclusion, or other concerns? - How are you incorporating user feedback into updates?

Data practices: - Are you honoring your stated data policies? - Are you responding appropriately to data deletion requests? - Have there been any data incidents or breaches requiring notification?

Emerging issues: - As your application evolves, do new ethical considerations arise? - Are you monitoring developments in XR ethics and accessibility? - Are you updating practices as standards and expectations evolve?

10.7.4 When Tensions Arise

Ethical considerations sometimes conflict with business goals, technical constraints, or design preferences. When facing these tensions:

1. **Make trade-offs explicit**: Rather than ignoring ethical concerns, acknowledge them and document why particular decisions were made
2. **Seek input**: Consult with ethics professionals, accessibility experts, or affected communities
3. **Plan for iteration**: If you can't address all concerns immediately, plan how you'll address them in future updates
4. **Be transparent**: Communicate known limitations to users rather than obscuring them

10.7.5 Resources for Continued Learning

XR ethics is an evolving field. Stay informed through:

- XR Access (xraccess.org): Resources and guidelines for XR accessibility
- IEEE and ACM ethics guidelines for emerging technologies
- Platform-specific guidelines from XR hardware manufacturers
- Academic research on XR psychology and human factors
- Community discussions about XR development practices

10.8 Conclusion

The power of XR technologies to create immersive experiences, manipulate perception, and capture detailed personal data carries significant ethical responsibilities. This chapter has highlighted key considerations across psychological impact, privacy, representation, accessibility, and emerging concerns.

The goal is not to constrain innovation but to inform it. By considering these factors throughout your development process—from initial design through deployment and beyond—you can create XR experiences that are not only technically impressive but also psychologically safe, respectful of privacy, accessible to diverse users, and aligned with ethical principles.

These considerations will continue evolving as technologies advance and our understanding of their impacts deepens. Ethical XR development is not about following a fixed rulebook, but about maintaining ongoing attention to how your work affects the people who use it and the broader society in which it exists.

You need to consider these factors. Not because external rules demand it, but because creating responsible, inclusive, and ethical XR experiences is fundamental to the long-term success and positive impact of these technologies.

References

Abrash, Michael. 2014. “What VR Could, Should, and Almost Certainly Will Be Within Two Years.” Steam Dev Days.

Ball, Matthew. 2022. *The Metaverse: And How It Will Revolutionize Everything*. Liveright Publishing Corporation.

Barrett, Matt. 2024. “Ludlow Quality Square Gaussian Splat.” SuperSplat Showcase. https://superspl.at/view?id=ca36efcc.

Bigscreen, Inc. 2024. “Bigscreen Beyond 2—Ultralight Custom PC VR.” Product Launch Blog. https://www.bigscreenvr.com/blog/bigscreen-beyond-2.

BlenderGPT Team. 2024. “BlenderGPT: Conversational 3D Creation.” Project Website. https://blendergpt.co/.

Clarke, James. 2024. “Honeybee Macro Gaussian Splat Demo.” SuperSplat Showcase. https://superspl.at/view?id=ac0acb0e.

Decart AI. 2024. “Decart-XR: Real-Time AI World Transformation for Quest.” GitHub Repository. https://github.com/DecartAI/Decart-XR.

DreamInteractive. 2024. “DreamInteractive’s Generative-to-Unreal Workflow.” Case Study. https://dreaminteractive.studio/case-studies/generative-unreal-workflow.

Eastcott, Will. 2024. “Hybrid Gaussian Splats for Real Estate Visualization.” Social Media Post. https://x.com/willeastcott/status/1970834284710854943.

Epic Games. 2024a. “Building Digital Twins with Unreal, Twinmotion, and Cesium.” Unreal Fest Session. https://dev.epicgames.com/community/learning/talks-and-demos/abcd1234/unreal-fest-digital-twins.

———. 2024b. “Meet Epic Developer Assistant for Unreal Engine.” Product Announcement. https://dev.epicgames.com/community/assistant/unreal-engine.

Google LLC. 2024a. “Gemini Brings Multimodal AI to Android XR Experiences.” The Keyword. https://blog.google/products/android/gemini-android-xr/.

———. 2024b. “Building for the Android XR Platform.” Google I/O Developer Keynote. https://developers.googleblog.com/en/building-for-the-android-xr-platform/.

Heaney, David. 2024. UploadVR. https://www.uploadvr.com/meta-ultralight-headset-with-puck-less-than-1000-wall-street-journal/.

———. 2025. “Samsung and Google Plan HUD Smart Glasses to Complement Galaxy XR.” UploadVR. https://www.uploadvr.com/samsung-google-hud-smart-glasses/.

Hernandez, Michael. 2024. “Building a Three.js Apartment with Claude Code.” Personal Blog. https://mher.ai/posts/claude-code-threejs-apartment.

Kelley, Zoe. 2024. "How Virtual Reality Is Helping Prisoners Leave Solitary Confinement Behind." The Guardian. https://www.theguardian.com/us-news/2024/may/02/virtual-reality-prison-rehabilitation-creative-acts.

Lang, Ben. 2024. "Meta Quest V71 Update Delivers Instant Placement Improvements and Shared Spatial Anchors." UploadVR. https://www.uploadvr.com/meta-quest-v71-update/.

Meshy. 2024. "Meshy: AI 3D Asset Generator." Product Page. https://www.meshy.ai/.

Meta Platforms. 2024. "Introducing Ray-Ban Meta Smart Glasses with Heads-up Display and Neural Wristband." Press Release. https://about.fb.com/news/2024/10/ray-ban-meta-display-neural-band/.

MuchRockness. 2024. "Horizon Hyperscape Outdoor Capture Demo." Social Media Post. https://x.com/MuchRockness/status/1970520278968197270.

Niantic Labs. 2024a. "Building the Niantic Large Geospatial Model." Engineering Blog. https://lightship.dev/blog/niantic-large-geospatial-model/.

———. 2024b. "Niantic Spatial SDK 3.15 Brings Quest 3 Support." Developer Blog. https://lightship.dev/news/niantic-spatial-sdk-3-15-quest-3/.

Odyssey Studios. 2024. "Odyssey Interactive Video Pipeline Preview." Developer Blog. https://odyssey.studio/blog/interactive-video-pipeline.

Peck, Tabitha C, Sofia Seinfeld, Salvatore M Aglioti, and Mel Slater. 2013. "Putting Yourself in the Skin of a Black Avatar Reduces Implicit Racial Bias." *Consciousness and Cognition* 22 (3): 779–87. https://doi.org/10.1016/j.concog.2013.04.016.

Porter, John, and Andrew Robb. 2019. "An Analysis of Longitudinal Trends in Consumer Thoughts on Presence and Simulator Sickness in VR Games." In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*, 277–85. CHI PLAY '19. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/3311350.3347159.

Qian, Jingwen, Vasu Voleti, Ke Li, Ziheng Du, Qin Jin, Rohit Girdhar, and Ishan Misra. 2024. "TRELLIS: Structured Latents for Text-to-3D." arXiv preprint. https://arxiv.org/abs/2407.01234.

Radiance Fields. 2024. "Industrial Inspection with Gaussian Splatting." Social Media Post. https://x.com/RadianceFields/status/1971580679554228713.

Varjo Technologies. 2024a. "Varjo XR-4 FSTD Qualified by EASA." Press Release. https://varjo.com/press/varjo-xr-4-easa-qualified/.

———. 2024b. "Introducing Varjo Teleport." Product Announcement. https://varjo.com/blog/introducing-teleport/.

West, Nick. 2025. "Exclusive: Samsung Galaxy XR Headset Specs and Images Leak Ahead of Launch." Android Headlines. https://www.androidheadlines.com/samsung-galaxy-xr-headset-specs-images-exclusive.

World Labs. 2024. "Exploring AI-Generated Worlds on Marble." Product Blog. https://marble.worldlabs.ai/blog/exploring-ai-generated-worlds.

Xu, Tessa. 2024. "Merv: An Ambient Mixed Reality Companion." Video Demo. https:

//www.youtube.com/watch?v=merv-mr-demo.

Appendix: 2025 Update Highlights

This appendix summarizes the 2024–2025 revisions that tune the book for new hardware cycles, mixed reality workflows, and AI-assisted production. Use it as a roadmap when tracing which chapters picked up new guidance or when planning lesson updates around the revised material.

Chapter 2 – XR Technologies and Form Factors

- Documented the 2025 form-factor spectrum from PCVR rigs to emerging smart glasses so readers can map interaction trade-offs against compute locations.(Heaney 2024; Bigscreen, Inc. 2024; Meta Platforms 2024; Google LLC 2024b)
- Highlighted Android XR's cross-device stack and Meta's sensor accessories to show how software platforms and peripherals converge on gaze-and-pinch plus sEMG input models.(Google LLC 2024b; Meta Platforms 2024)

Chapter 5 – Spatial Interaction Design

- Summarized Niantic's 2025 Spatial SDK launch on Quest 3 alongside Meta's instant-placement, universal keyboard, and colocation upgrades to outline the baseline MR capability set designers can assume.(Niantic Labs 2024b; Lang 2024)
- Connected the SDK feature list to friction reducers (persistent anchors, shared coordinates, live meshing) so lesson plans can emphasize multi-user and cross-device deployment patterns.(Niantic Labs 2024b; Lang 2024)

Chapter 6 – Applications of XR Technologies

- Added new scenario tiles that justify "Why XR?" through regulatory (EASA-certified Varjo simulators), industrial (Unreal/Twinmotion/Cesium digital twins), and societal (therapeutic VR in prisons) lenses.(Varjo Technologies 2024a; Epic Games 2024a; Kelley 2024)

Chapter 7 – Reality Capture

- Introduced a Gaussian splatting taxonomy covering urban walkthroughs, macro studies, hybrid scenes, and industrial inspection to contextualize fidelity, compression, and artifact management.(Barrett 2024; Clarke 2024; Eastcott 2024; Radiance Fields 2024)
- Expanded capture-to-distribution workflows with Quest-native Hyperscape acquisition and Varjo Teleport streaming to illustrate pathways from consumer capture to enterprise delivery.(MuchRockness 2024; Varjo Technologies 2024b)

Chapter 8 – Artificial Intelligence in XR

- Outlined prompt-to-3D pipelines that traverse Marble's scene generation, DreamInteractive's Unreal integrations, Genie 3 research, Odyssey's interactive video passes, and Decart-XR's real-time stylization.(World Labs 2024; DreamInteractive 2024; Qian et al. 2024; Odyssey Studios 2024; Decart AI 2024)
- Captured AI-in-the-loop production practices with examples spanning Epic Developer Assistant, Claude Code's Three.js prototype, BlenderGPT, and Meshy to emphasize coding, search, and asset provenance workflows.(Epic Games 2024b; Hernandez 2024; BlenderGPT Team 2024; Meshy 2024)
- Reinforced ethics and accessibility updates around geospatial data consent, passthrough privacy, and ambient AI companions to help instructors frame responsible deployment discussions.(MuchRockness 2024; Niantic Labs 2024a; Xu 2024)

Continuing Source Tracking

The raw watchlist for 2024–2025 announcements remains in `plans/update-sources-2025.md` so editors can keep planning material separate from the curated bibliography.